Lattice QCD - an Interacting Hadron Resonance Gas ?

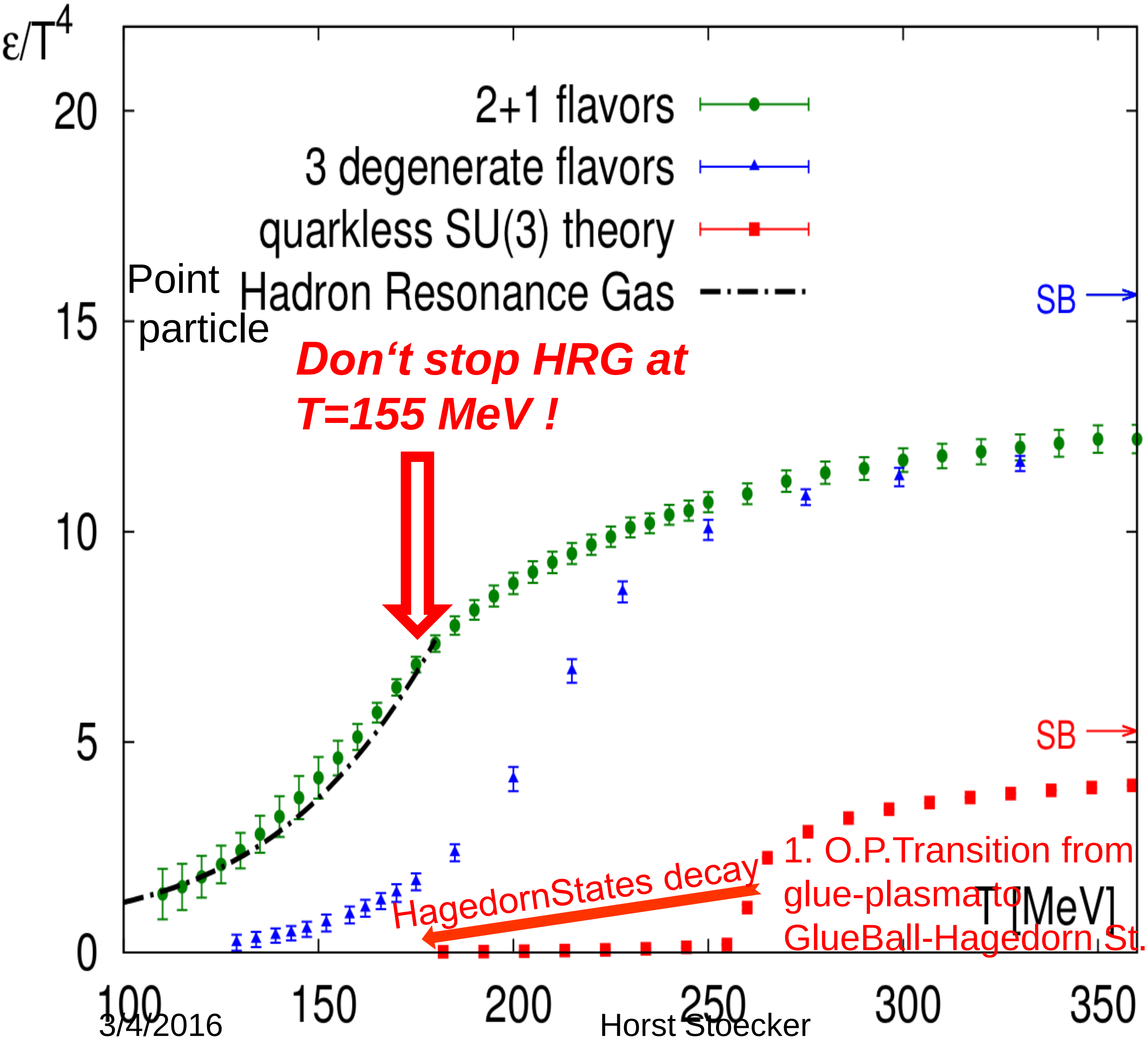
Entropy density, pressure, entropy, Chi_B,Q,S of interacting HRG = Lattice QCD (WB-data, Borsanyi et al.)

No Phase Transition at T_c = 155 MeV of 2+1 Flavor QCD !

Interact. Hadron Resonance Gas describes lattice QCD well up to T~250 MeV, mix w. HTL QGP at higher T

Trace anomaly, interaction measure, nonperturbative effects the role of 'Hot Hadrons' ?

2+1 flavor Lattice QCD and Pure Yang Mills LGT
Energy density (EoS) DIFFERENT for different quark masses



Point particle

Don't stop HRG at T=155 MeV !

HagedornStates decay

1. O.P.Transition from glue-plasma to GlueBall-Hagedorn St.

Energy density from Sz. Borsanyi et al.W.B. Wuppertal-Budapest c

JHEP 1011, 2010,077;
PLB730, 2014, 99

(2+1)- flavor QCD is matched by

N_f = 3, $m_{u,d} = m_s$

at T = 250 MeV

pure gauge, YangMills

T_c = 270 MeV

Quenched: W.B. coll.
JHEP 1207, 2012, 056

Multi-component Eigenvol. HRG constrained by lattice QCD data

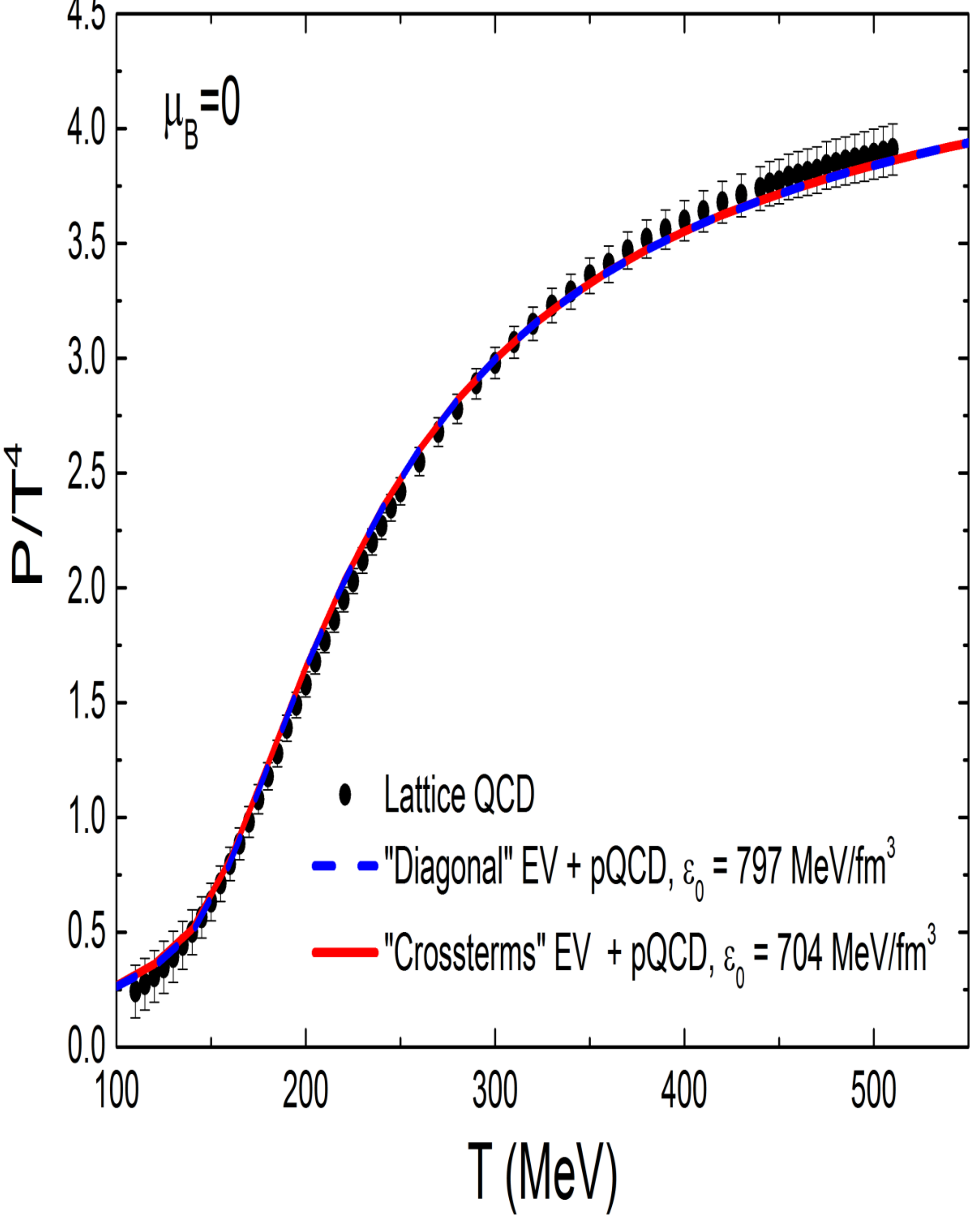
Crossover QCD-EoS matches **HRG at low (T,μ)** + pert. QCD at high (T,μ)

AKY, Kapusta group
PRC 90024915 (2014)

$$p(T,\mu) = [1 - S(T,\mu)]P_{HRG}(T,\mu) + S(T,\mu)P_{pQCD}(T,\mu)$$

Transition from
EV HRG ($r_i \sim m_i^{1/3}$)
to pQCD
at $T_0 \cong 175$ MeV
via switching function

Fit $T < T_0$ $r_p = 0.43$ fm - Consistent with lattice



Lattice QCD = Interacting Hadron Resonance Gas ?

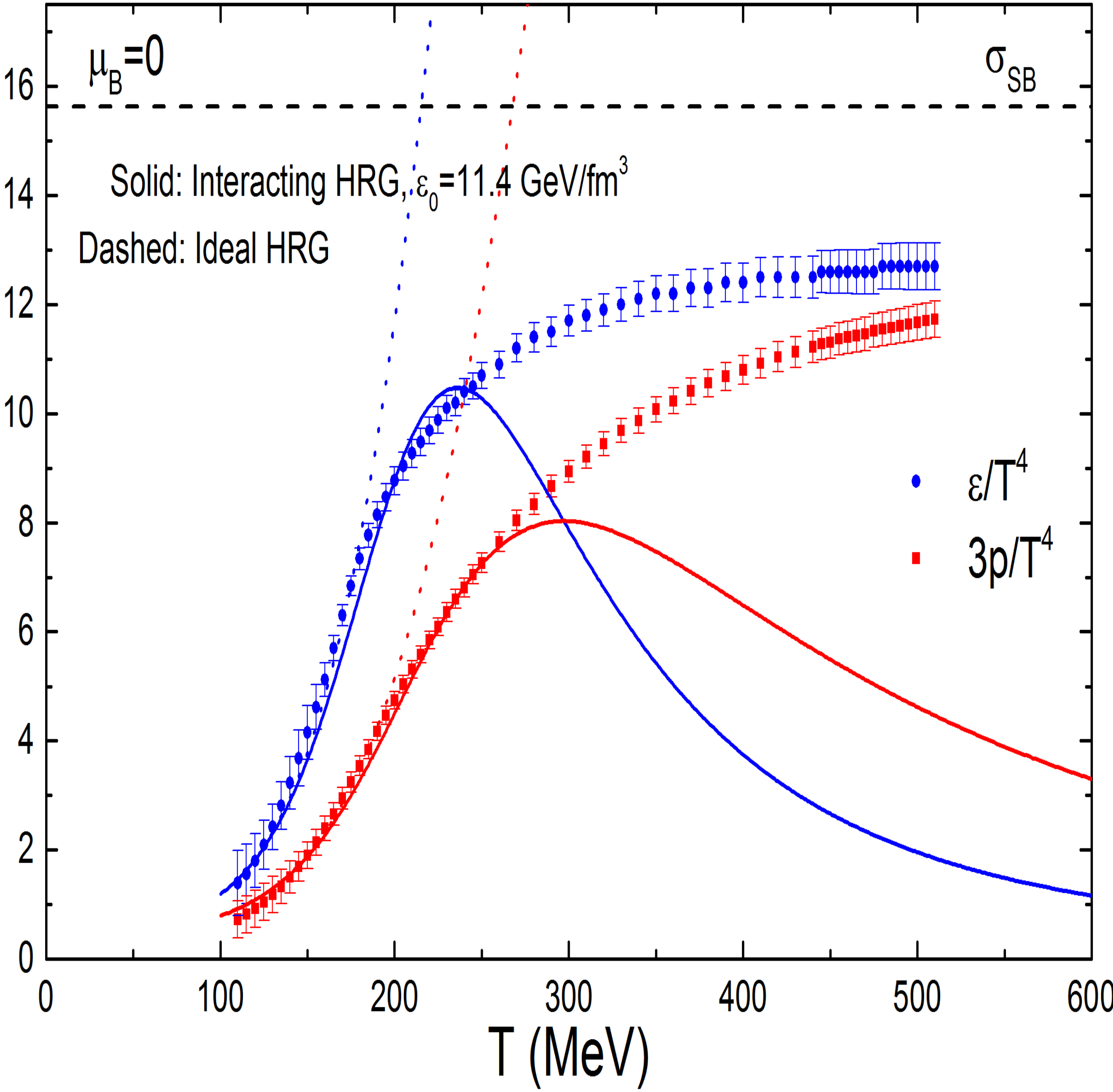
Lattice QCD fit
up to T~ 250 MeV
by ***interacting* HRG**
Eigenvolume $v_i = m_i/\varepsilon_0$

“Crossterms” EV model

$$p = \sum_i \frac{T n_i}{1 - \sum_j \tilde{b}_{ji} n_j}$$

$$\tilde{b}_{ij} = \frac{2 b_{ii} b_{ij}}{b_{ii} + b_{jj}}$$

$$b_{ij} = \frac{2}{3}\pi\left(r_i + r_j\right)^3$$

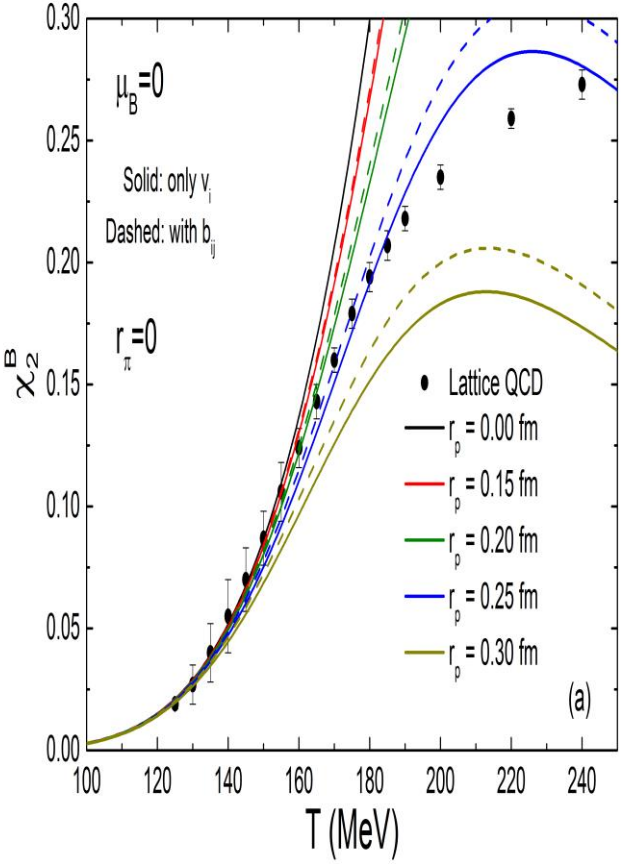


V. Vovchenko, H.ST

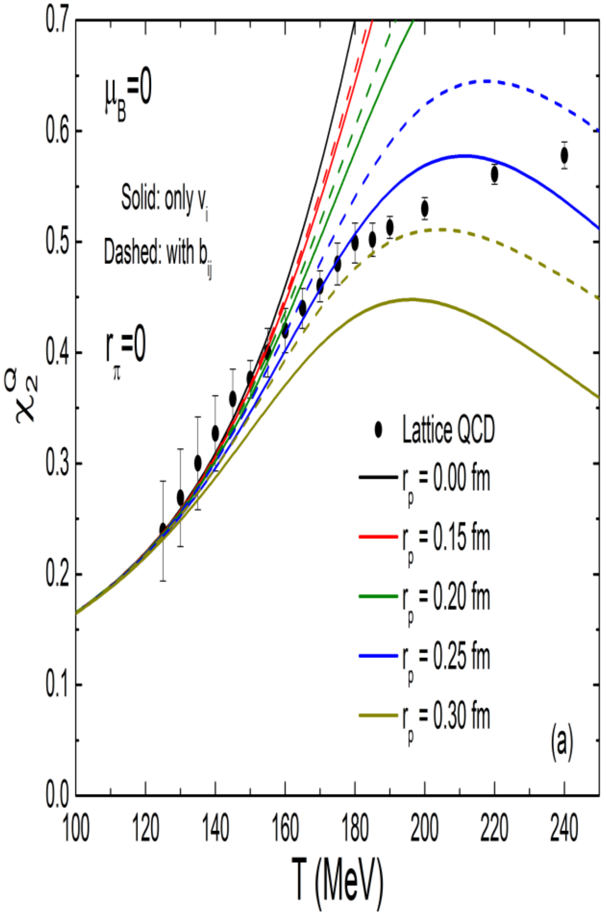
Multi-component bag-eigenvolume HRG vs lattice QCD

Susceptibilities carry information about fine details of the equation of state

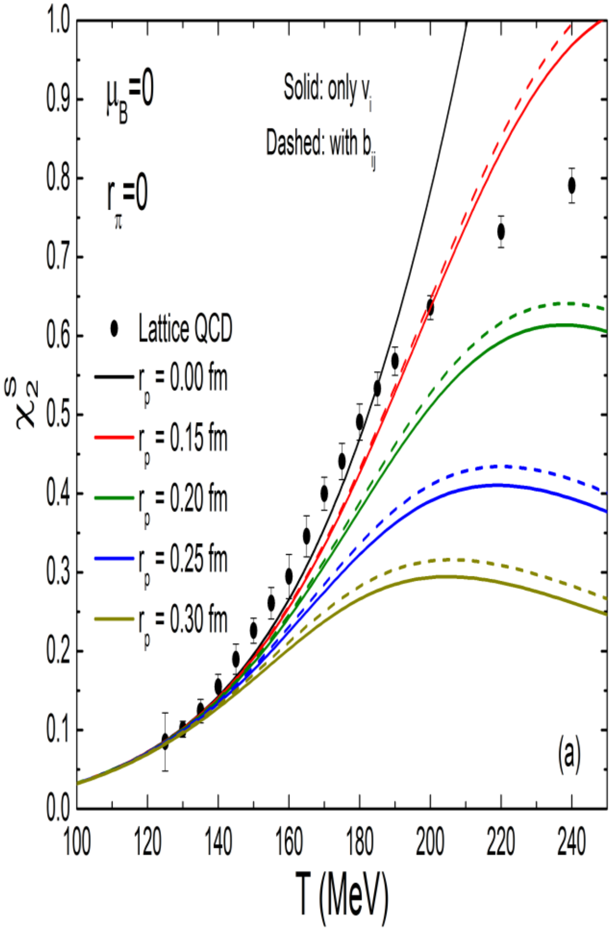
χ_2^B



χ_2^Q



χ_2^S



r=0 : HRG of point particles
cannot follow lattice data above T=160 MeV
Finite eigenvolumes of hadron bags:
dramatic improvement towards lattice data

strange vs non-strange hadrons
different volumes at same mass?

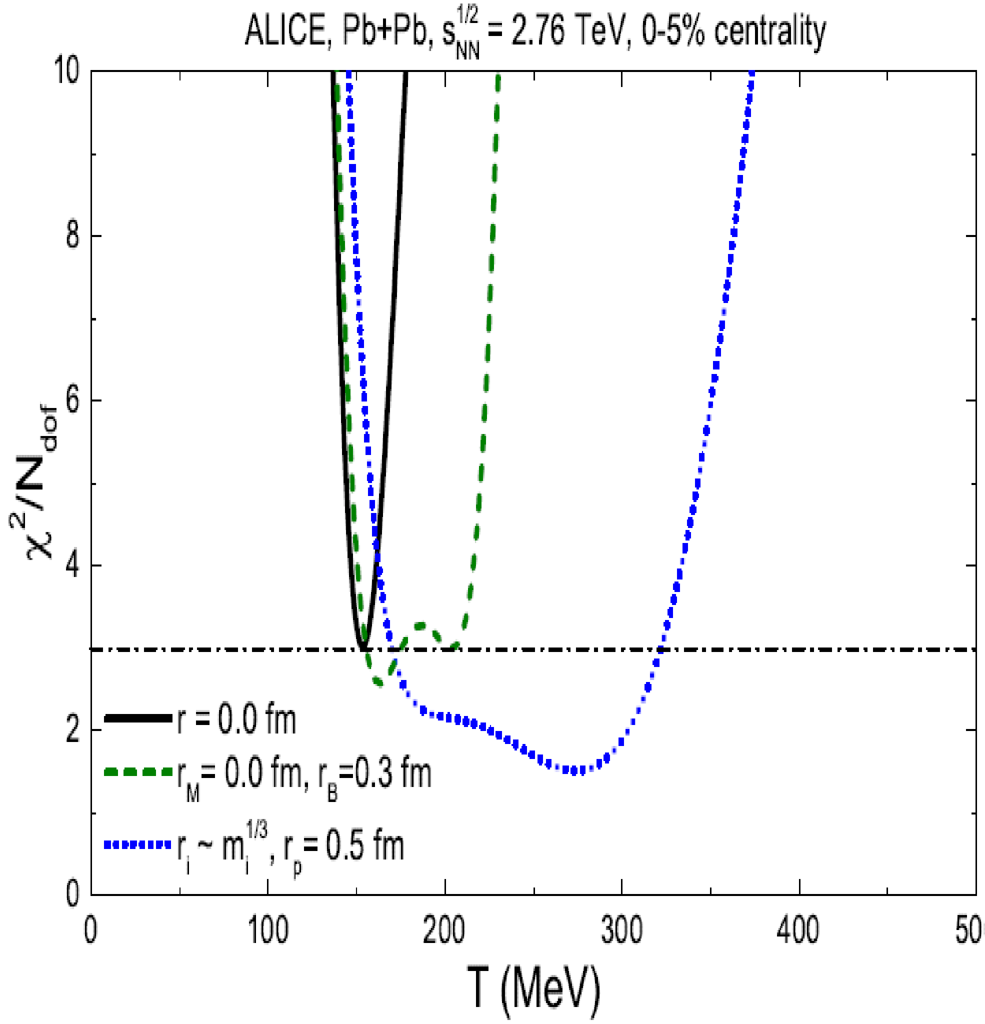
V. Vovchenko, H.ST

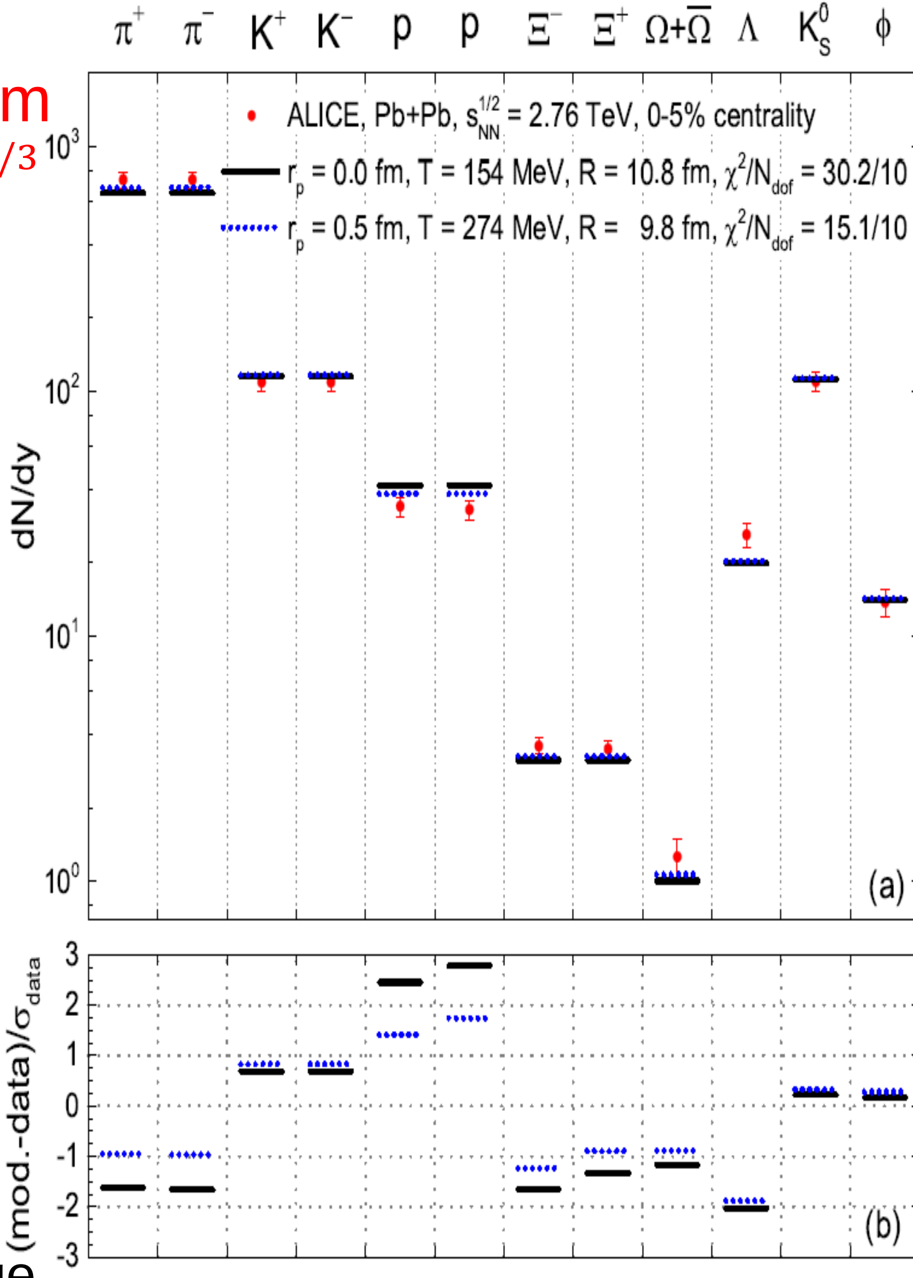
Multi-component Eigenvol. HRG vs ALICE hadron yield data

Two diff. Eigenvolume parametrizations:

AA Point-like mesons, Baryons $r_B = 0.3$ fm

AKYBag-model inspired EV model: $r_i \sim m_i^{1/3}$





ALICE yield data fit wide temperature range

two different eigenvolumes parametrizations

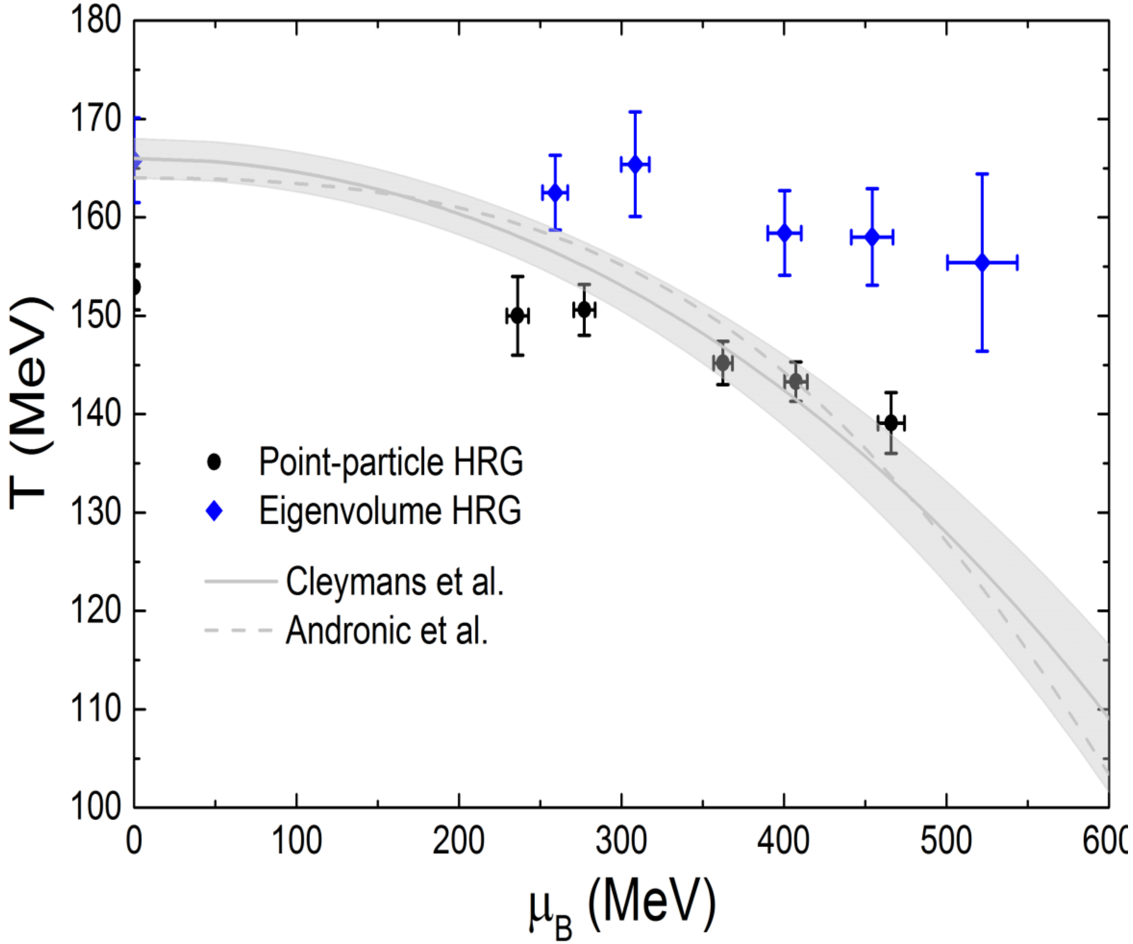
Vovchenko,HST1512.08046 [hep-ph]

Multi-component eigenvol. HRG constrained by lattice data

Crossover QCD-EoS matched by **HRG at low (T, μ)** + pert. QCD at high (T, μ)

$p(T,\mu) = [1 - S(T,\mu)]P_{HRG}(T,\mu) + S(T,\mu)P_{pQCD}(T,\mu)$ AKY PRC90024915’14

Transition from EV HRG ($r_i \sim m_i^{1/3}$) to pQCD at $T_0 \cong 175$ MeV via switching functi

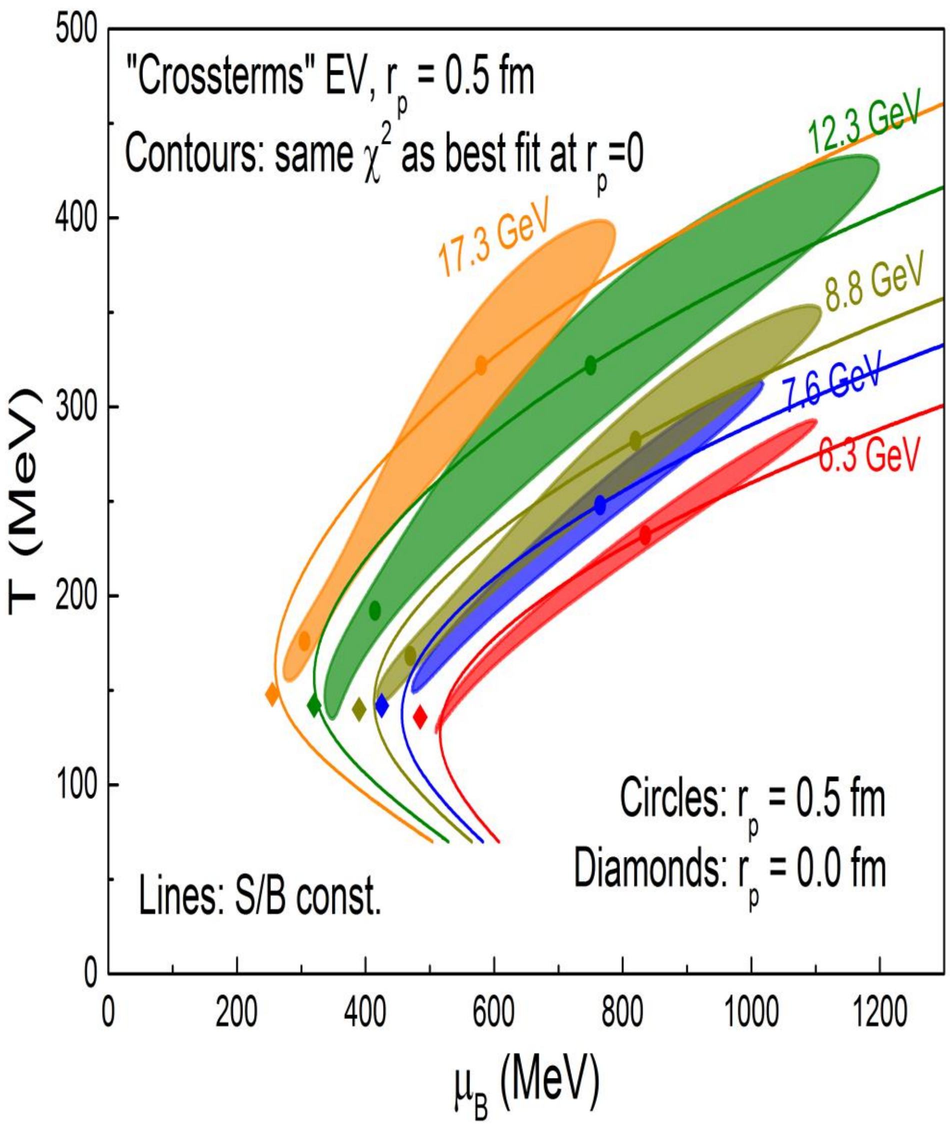


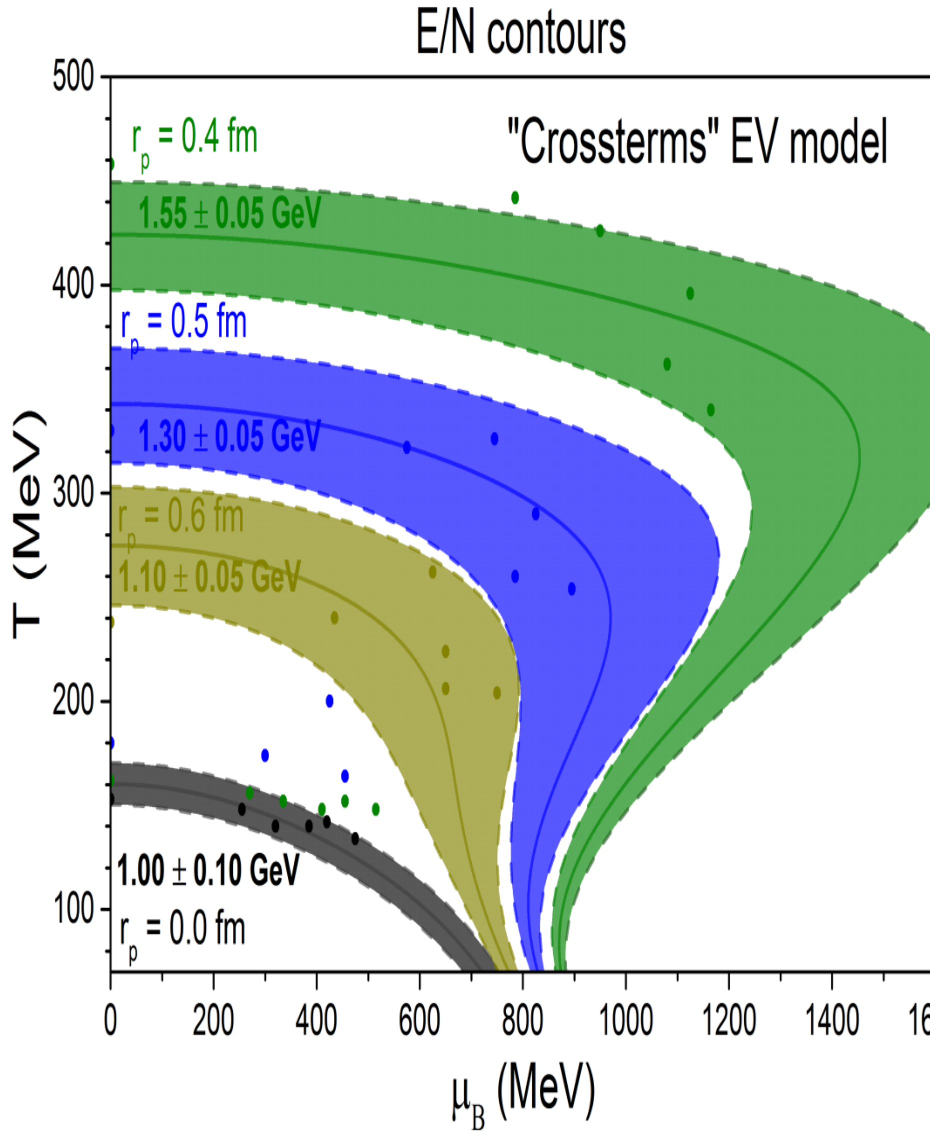
systematically better χ^2 at higher freeze-out T and μ

Fit to yield data at $T < T_0$ with $r_p = 0.43$ fm - Consistent with lattice Vovchenko

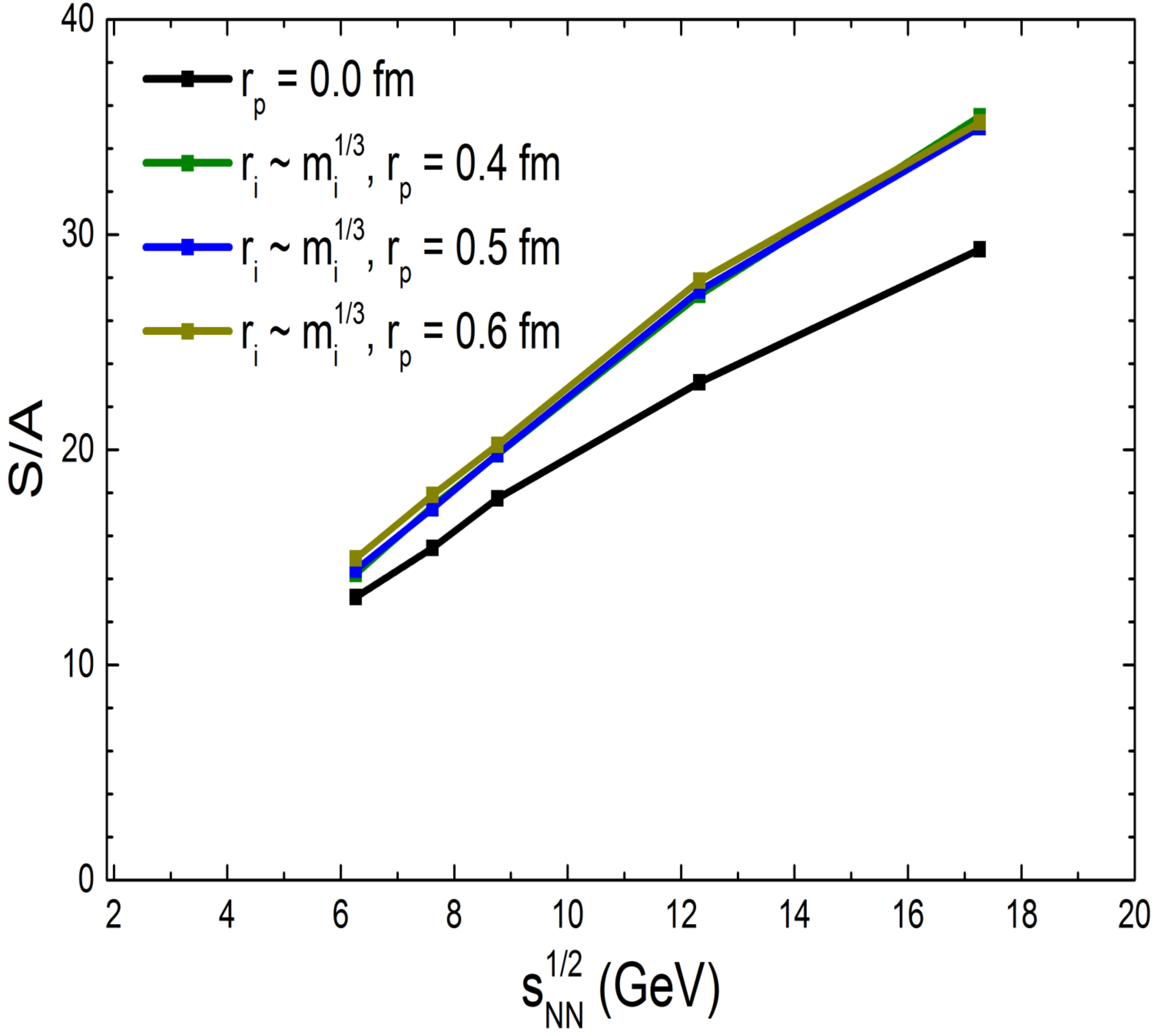
Multi-component eigenvol. HRG vs NA49 hadron yield data

Bag-model inspired EV model: $r_i \sim m_i^{1/3}$ Vovchenko,HS





freeze-out parameters extraction with int.HRG does yield unique S/A fits !



VoVchenko: NA49 data allow measurement of S/A= const (energy)!

Acknowledgements

Transport: Zhou, Seizel, Xu, Nara, Pang, Niemi, Biro, C. Greiner...

Hagedorn: Beitel, Gallmeister, Vovchenko, Hostler, C. Greiner...

FIAS: Schramm, Steinheimer, Struckmeier, Vasak, ...

Early phase EM probes : Vovchenko, Satarov, Gorenstein, Mishustin, Csernai, Raha, Sinha, ...

Lattice : Borsanyi, Fodor, Szabo, Karsch, Panero, Philipsen, Ratti

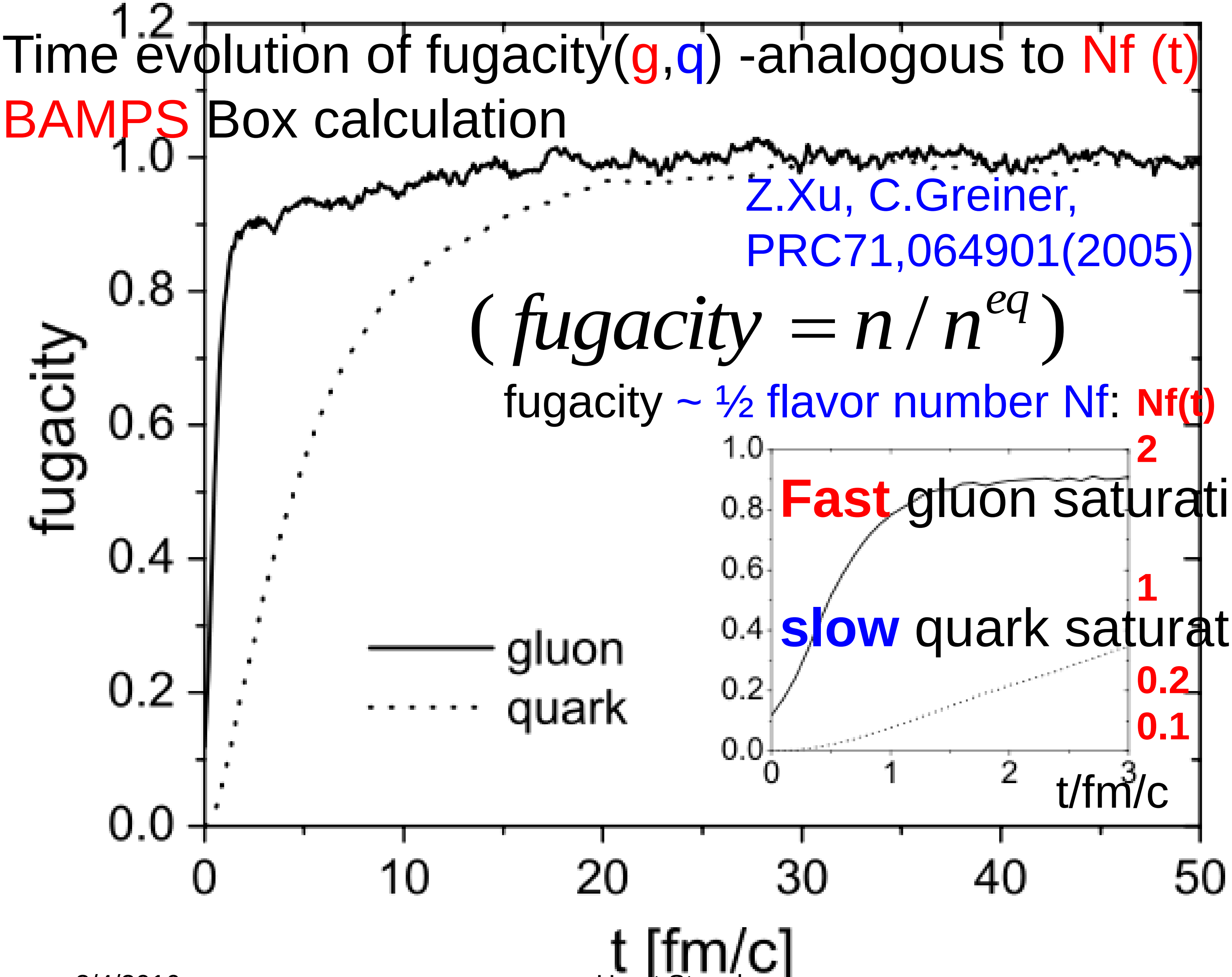
ALICE: Giubellino, Harris, Andronic, Bellwied, PBM, Loiz. Masc.

Signatures for pure glue => glueball scenario

New event-class in high multiplicity pp & pA at FAIR*, RHIC and LHC

Time evolution of fugacity(g,q) -analogous to Nf (t)

BAMPS Box calculation



Z.Xu, C.Greiner,
PRC71,064901(2005)

$$(fugacity = n / n^{eq})$$

fugacity ~ ½ flavor number Nf: **Nf(t)**

2

Fast gluon saturation,

1

slow quark saturation

0.2

0.1

t/fm/c

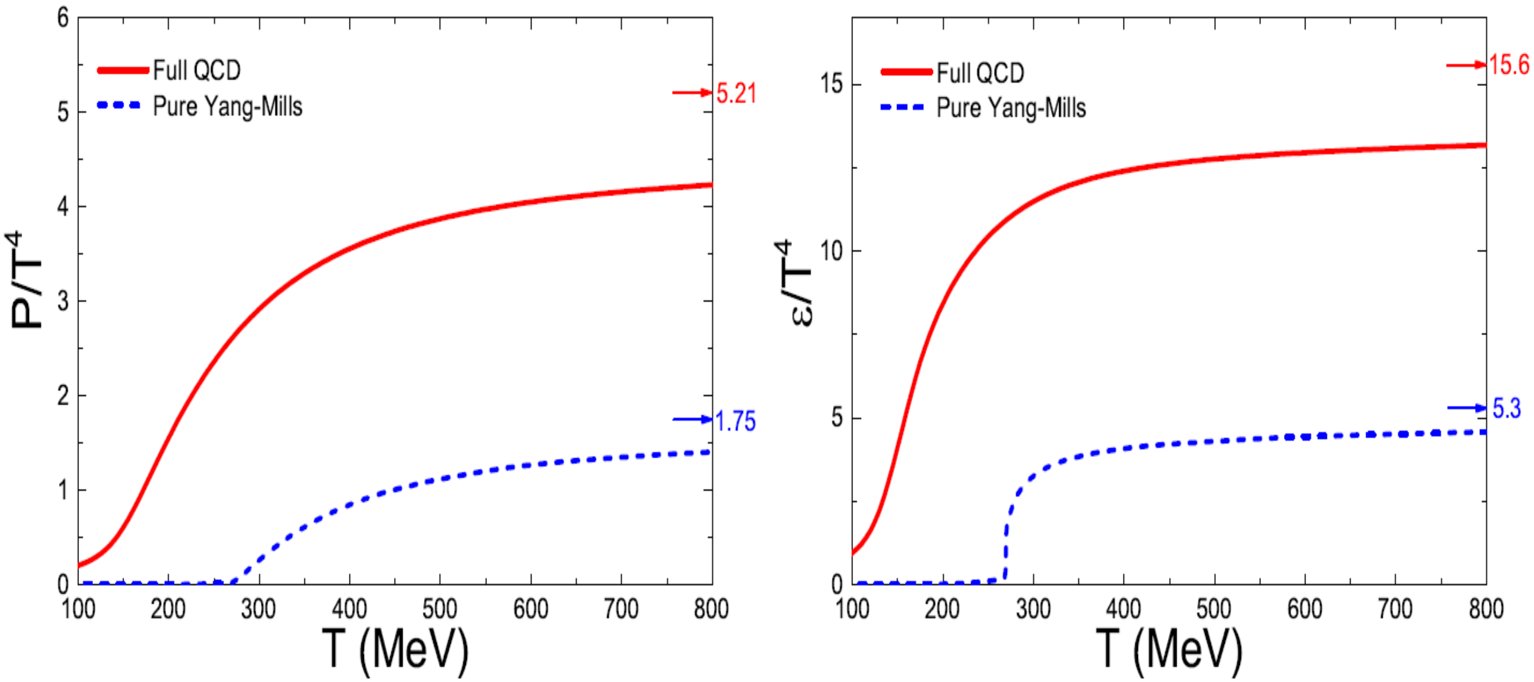
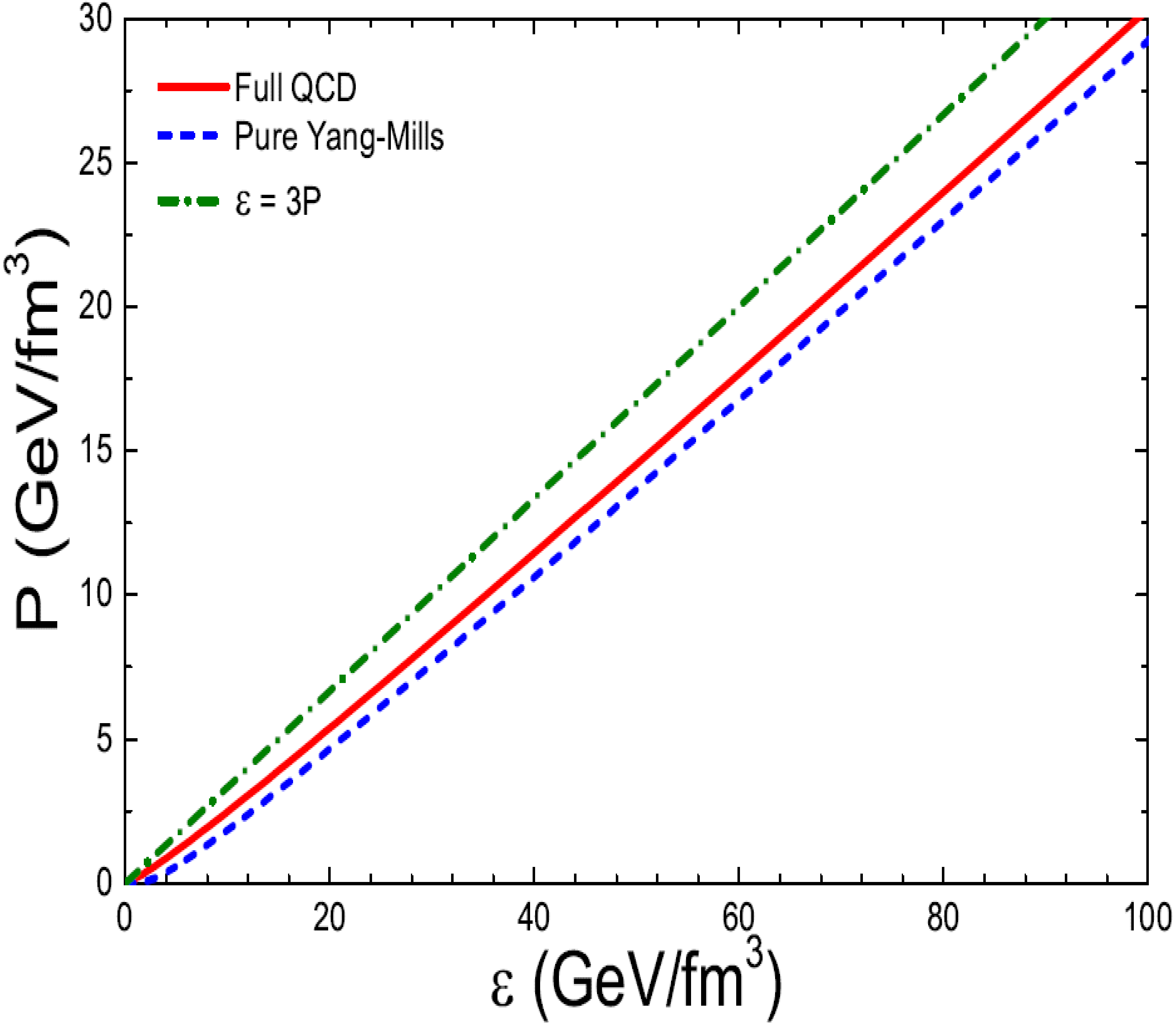
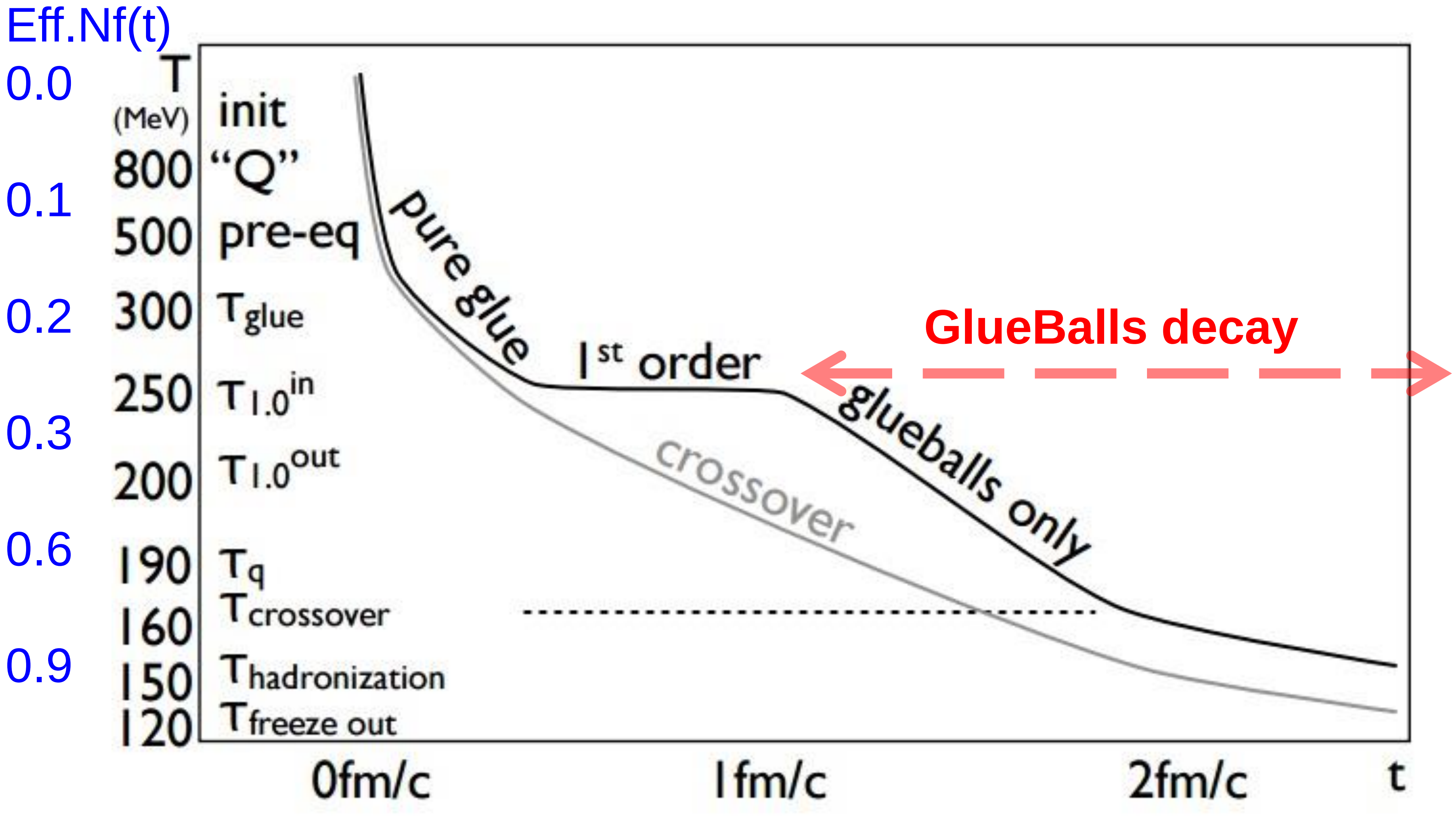


FIG. 1: (Color online) Temperature dependence of the scaled pressure (a) and energy density (b) obtained in lattice QCD calculations of Refs. [28, 31]. The solid and dashed lines correspond to the FQ ($N_f = 2+1$) and PG ($N_f = 0$) cases, respectively. The horizontal arrows indicate the asymptotic (Stefan-Boltzmann) values of P/T^4 and ε/T^4 at large temperatures.

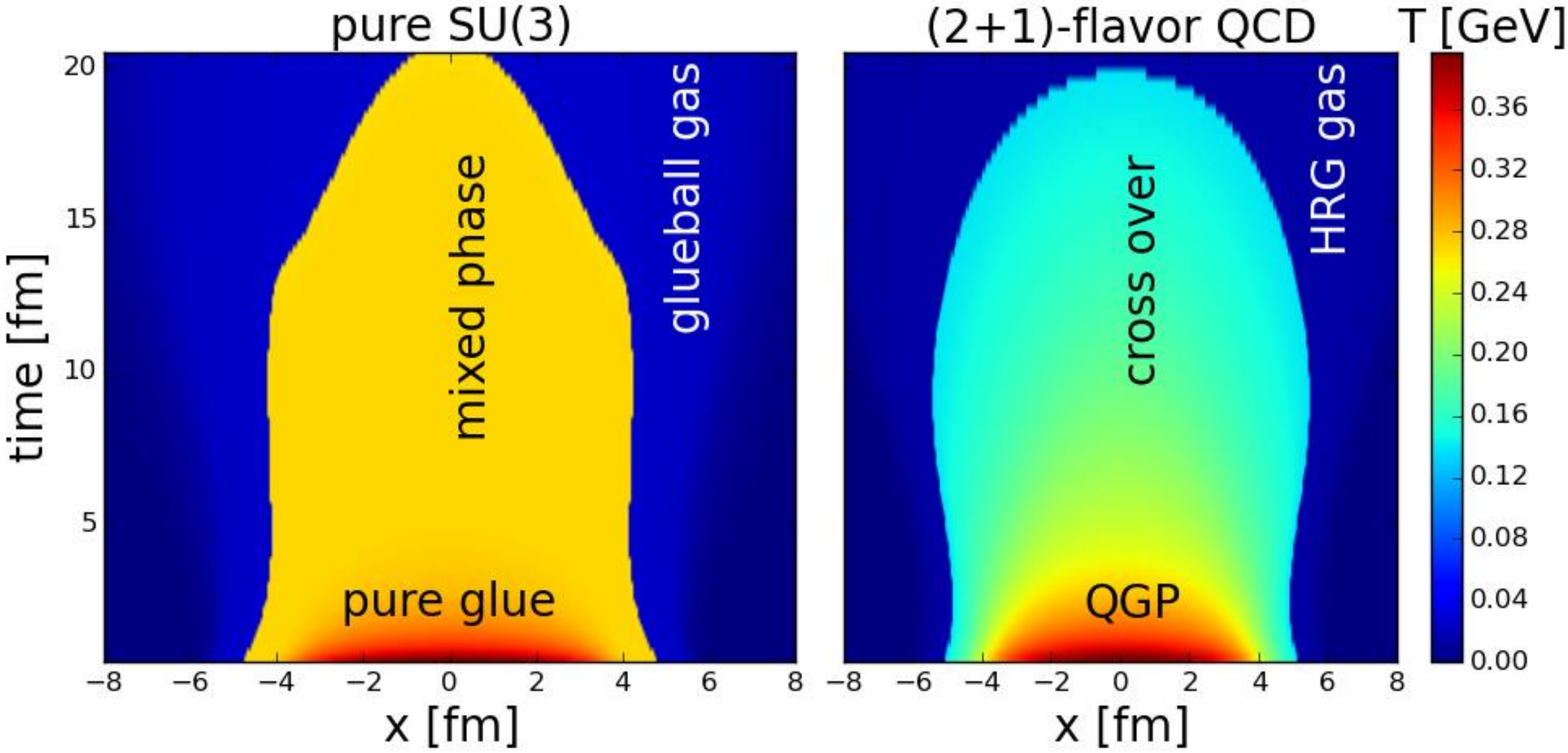

Full QCD
Pure Yang-Mills
ε = 3P
P (GeV/fm^3)
ε (GeV/fm^3)
0
5
10
15
20
25
30
0
20
40
60
80
100



Eff. Nf(t): 0 0.1 0.2 0.3 0.6 1.2 ...

Eff. Nf(t) is U.S. – parameter : Nf = 2+1 ~ fugacity = 1

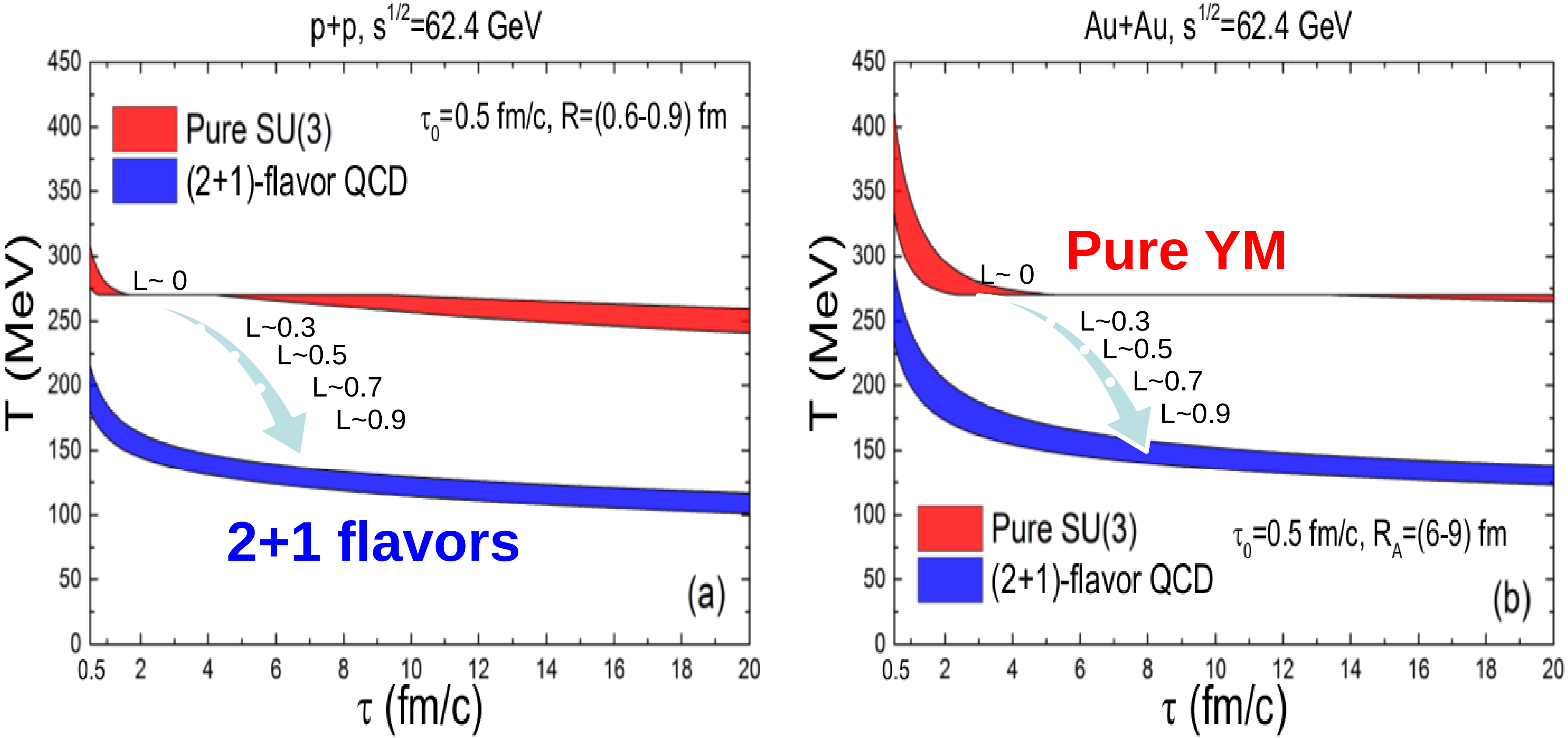
Hydrodynamic expansion of pure glue and QGP with the 2 different EoS



- **Energy density smaller than 0.15 GeV is masked as HRG or glueball fluid**
- **The mixed phase lasts very long with pure SU(3) gauge EOS**

LongGang Pang, V. Vovchenko, H. Niemi, HST

Time evolution T(t) of pp vs AA collisions at RHIC



Pure YM

2+1 flavors

FIG. 3: (Color online) The τ-dependence of the temperature for QGP and pure SU(3) scenarios in (a) p+p and (b) $A+A$ collisions at $\sqrt{s_{\mathrm{NN}}} = 62.4$ GeV. The uncertainty bands result from variation of the transverse radius.

V. Vovchenko et al.

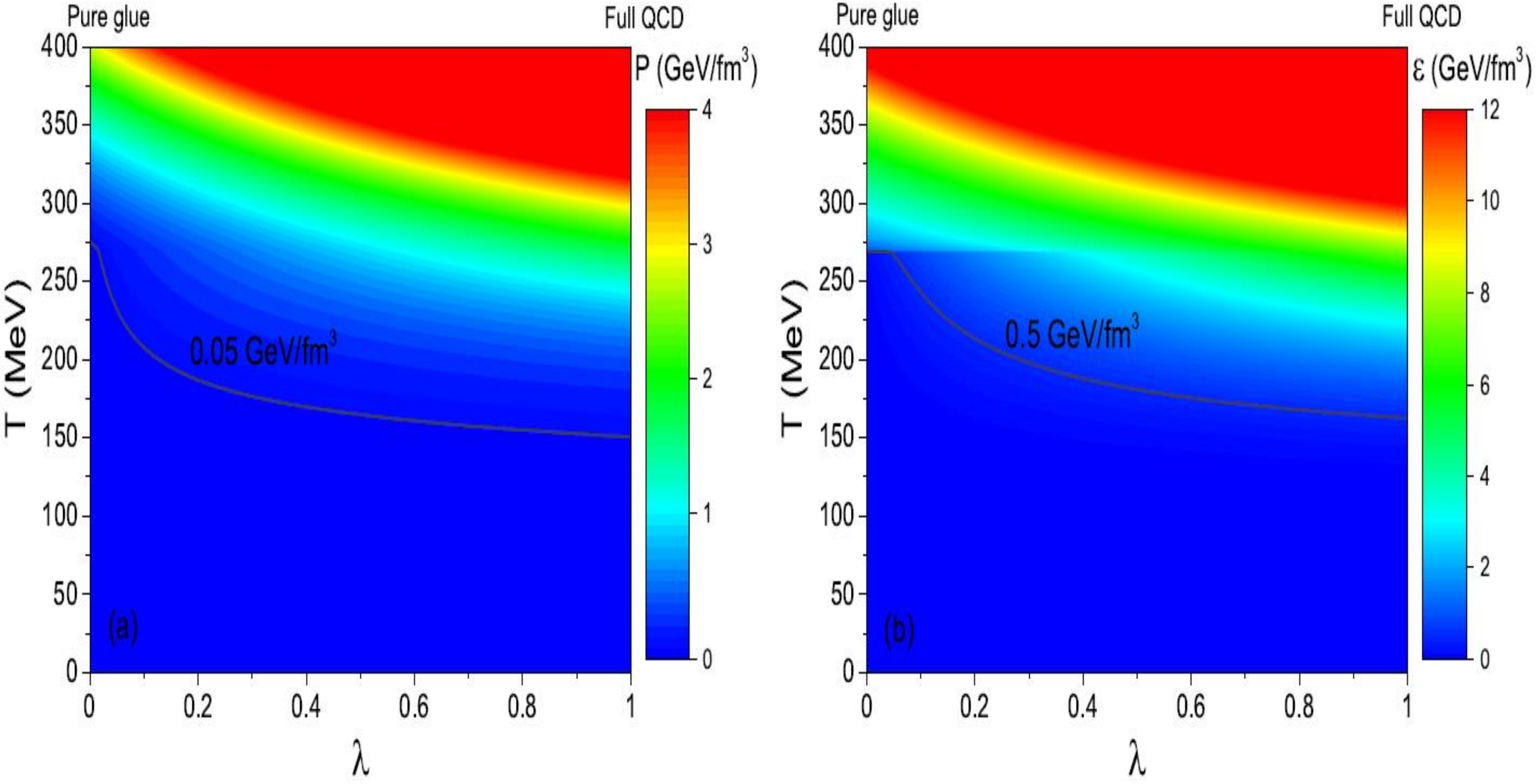


FIG. 3: (Color online) Density plots of pressure (a) and energy density (b) for chemically non-equilibrium QGP calculated from Eqs. (5) and (6). The solid lines show contours $P = 0.05\ \mathrm{GeV/fm^3}$ (a) and $\varepsilon = 0.5\ \mathrm{GeV/fm^3}$ (b).

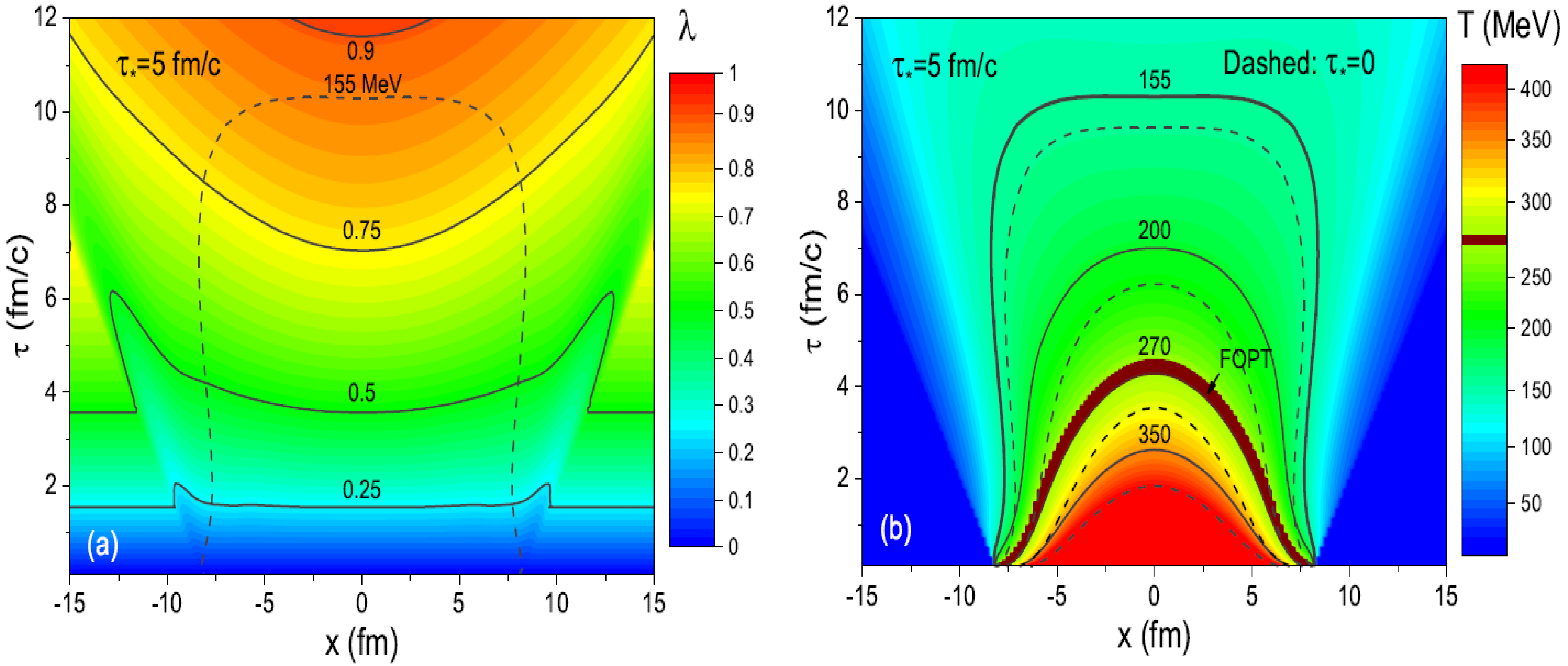


FIG. 4: (Color online) Density plots of the quark fugacity (a) and temperature (b) in the $x-\tau$ plane for the 0–20% most central Pb+Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV. The solid lines show contours of λ and T (in MeV). The dashed line in (a) corresponds to the isotherm $T=155$ MeV. The dark region labeled by FOPT corresponds to the mixed-phase region of the first-order phase transition at $T=T_c\simeq$ 270 MeV. The dashed lines in (b) are isotherms calculated for equilibrium

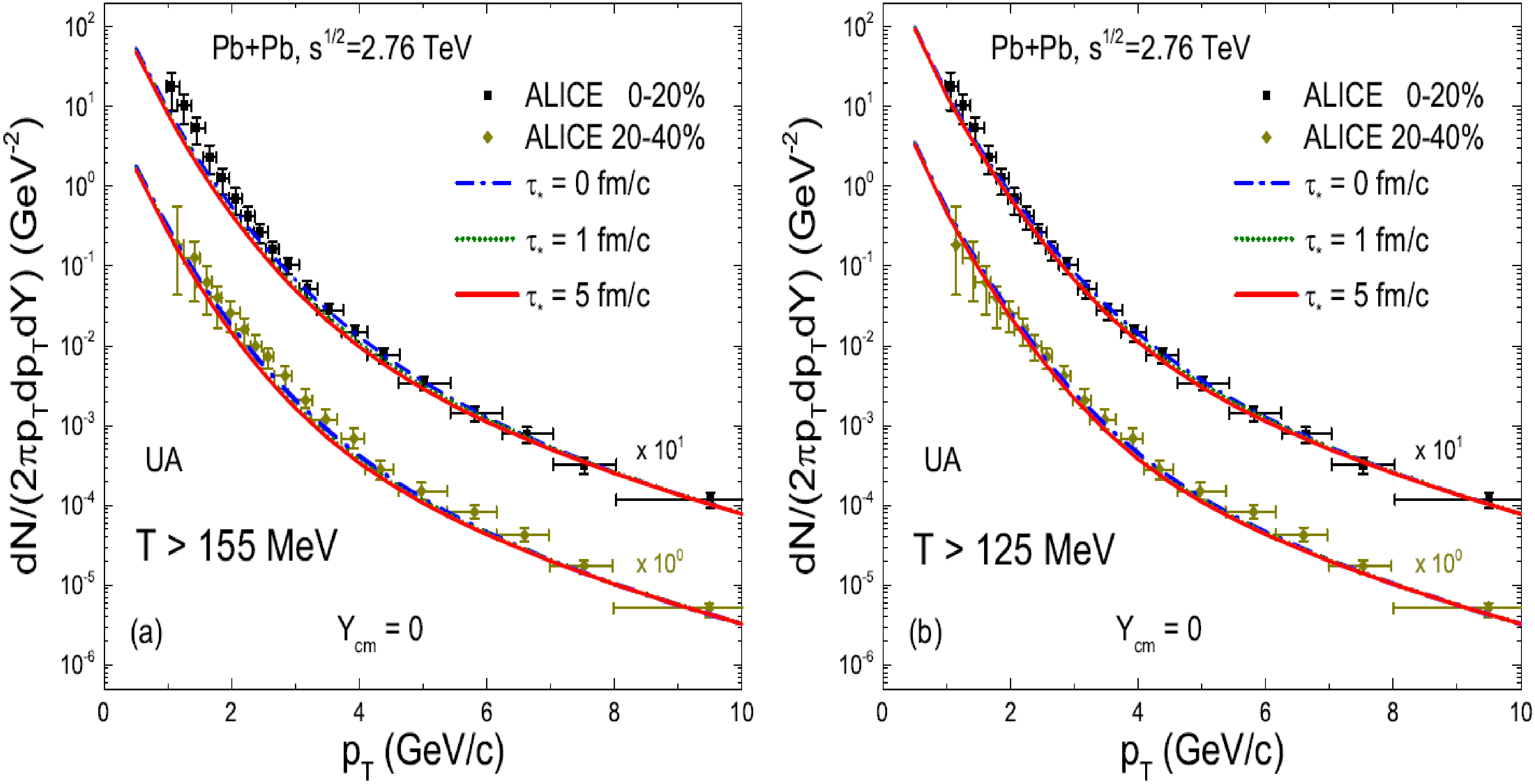


FIG. 8: (Color online) Spectra of direct photons in the 0–20% central Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV calculated using Eqs. (13)–(14) with the cutoff temperatures $T_f = 155$ (a) and 125 (b) MeV. The dash-dotted, dotted and solid lines correspond to $\tau_* = 0, 1$ and 5 fm/c, respectively. Dots with error bars show experimental data [42].

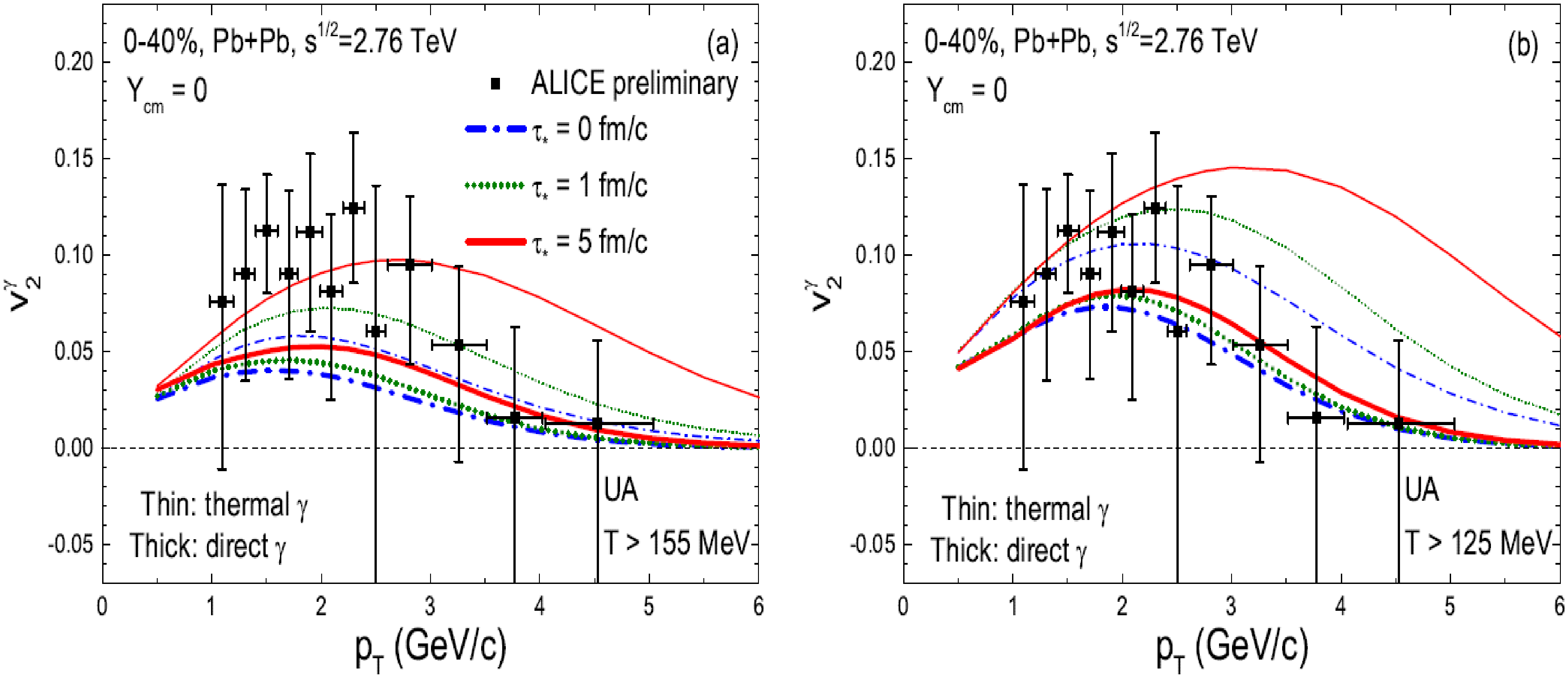


FIG. 9: (Color online) Elliptic flow of direct photons as a function of transverse momentum in the 0–40% central Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV calculated with the cutoff temperatures $T_f = 155$ (a) and 125 (b) MeV. The dash-dotted, dotted and solid lines correspond to $\tau_* = 0, 1$ and 5 fm/c, respectively. Thick (thin) curves are calculated with (without) the contribution of prompt photons in Eq. (15). Data are taken from Ref. [39].

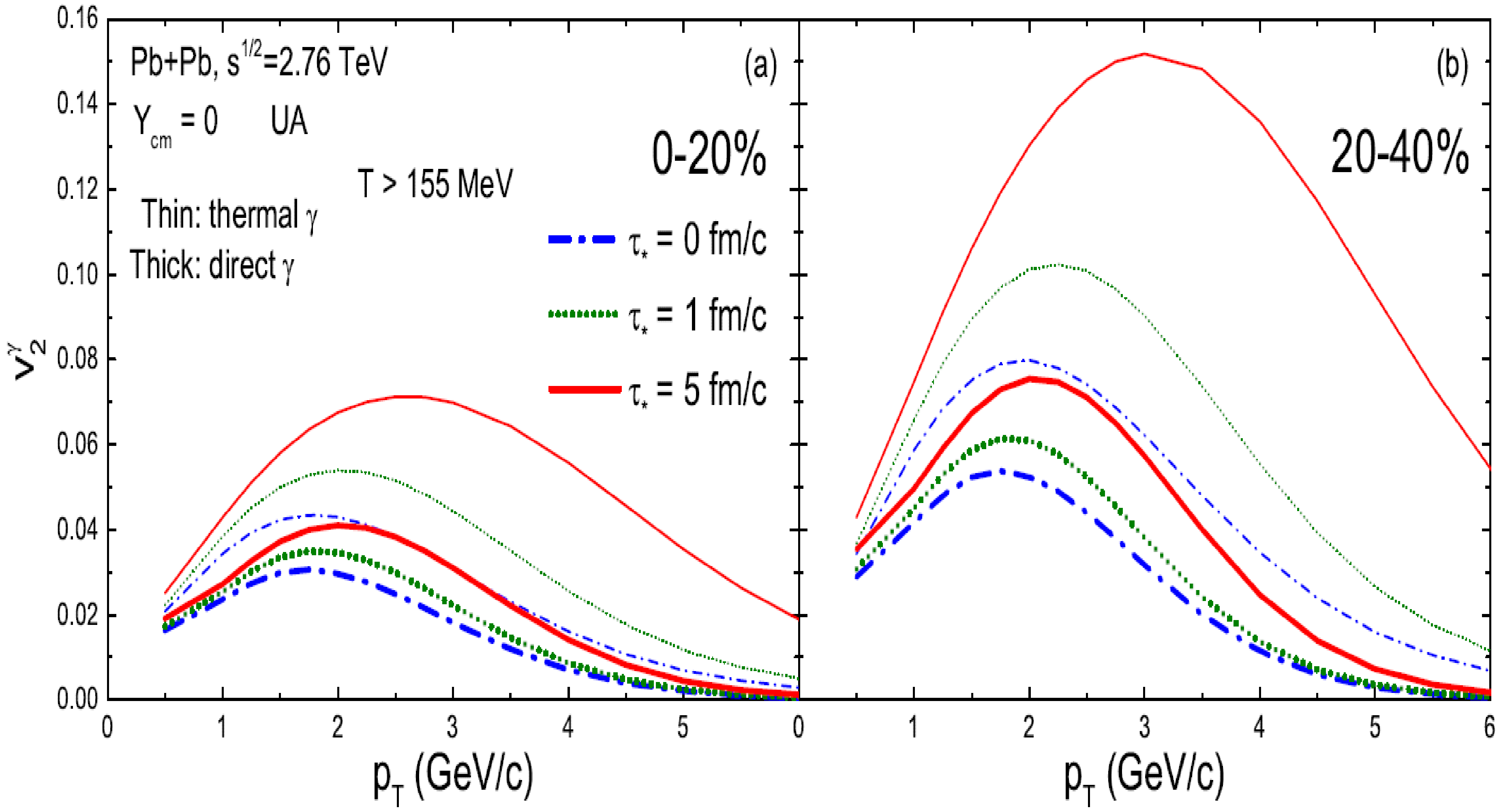


FIG. 10: (Color online) Elliptic flow of the direct (thick lines) and thermal (thin lines) photons for the 0–20% (a) and 20–40% (b) central Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV.

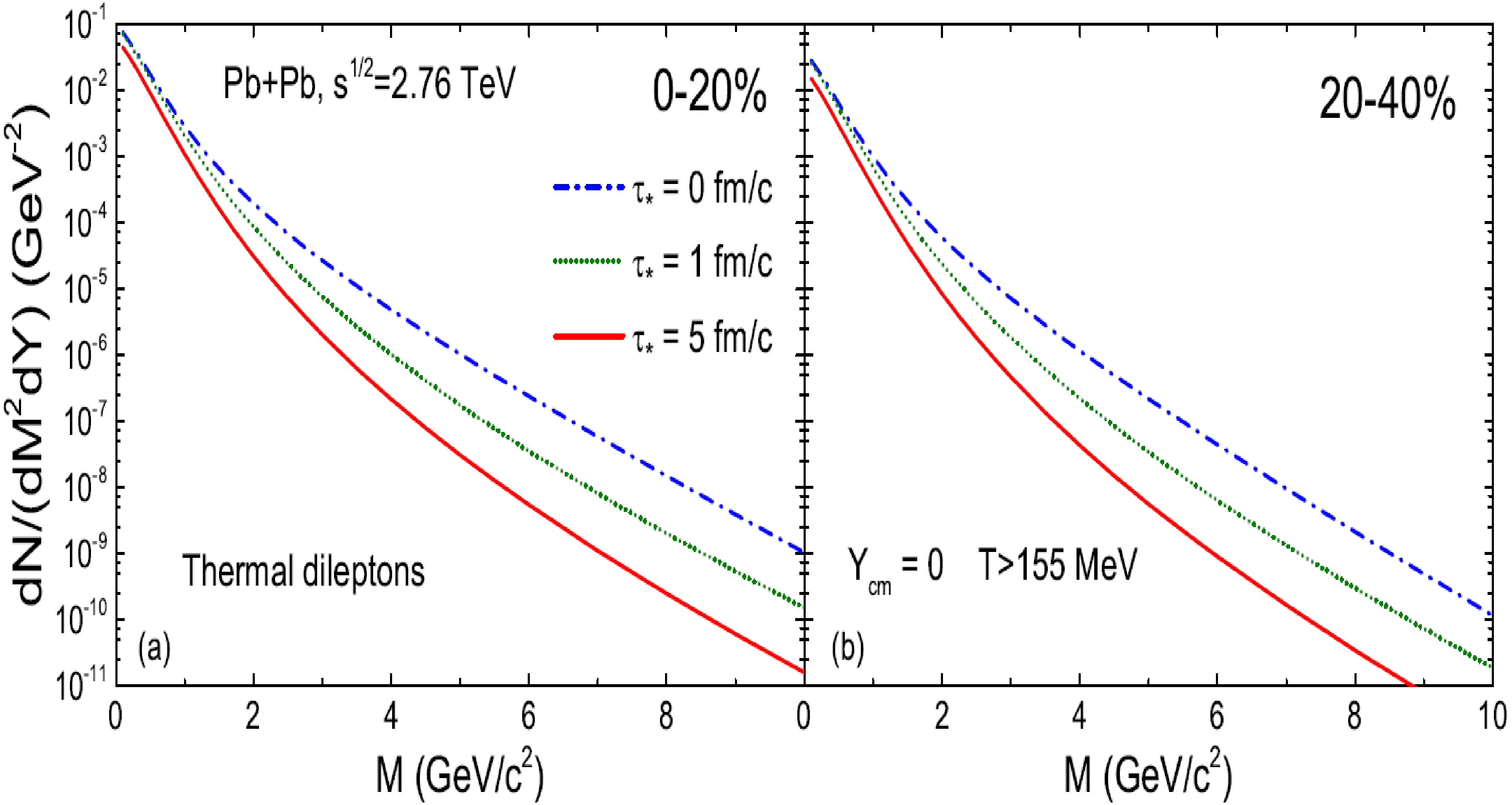


FIG. 11: (Color online) Invariant mass distribution of thermal dileptons in the 0–20% (a) and 20–40% (b) central Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV calculated for $\tau_* = 0, 1$ and 5 fm$/c$. All results correspond to the cut-off temperature $T_f = 155$ MeV.

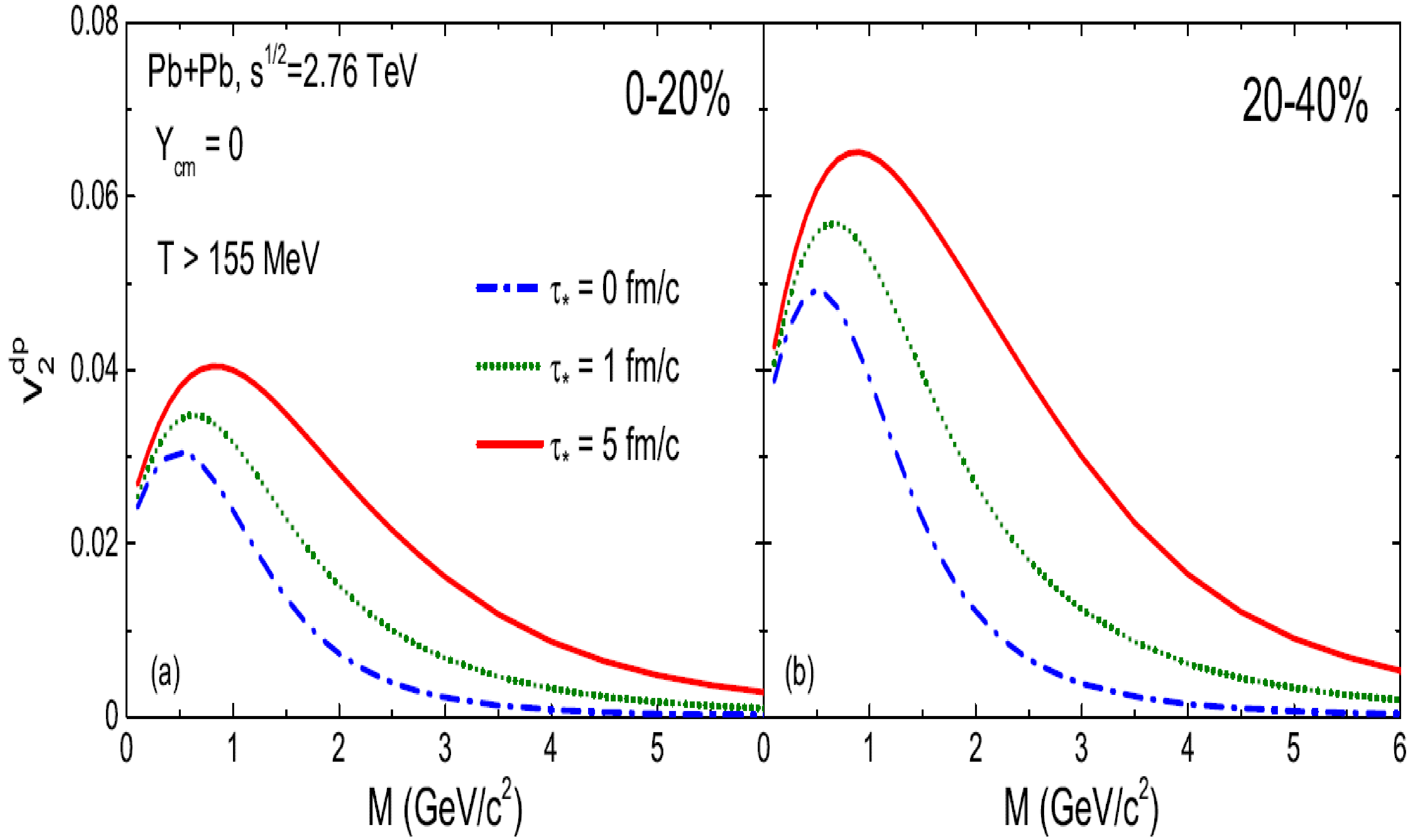
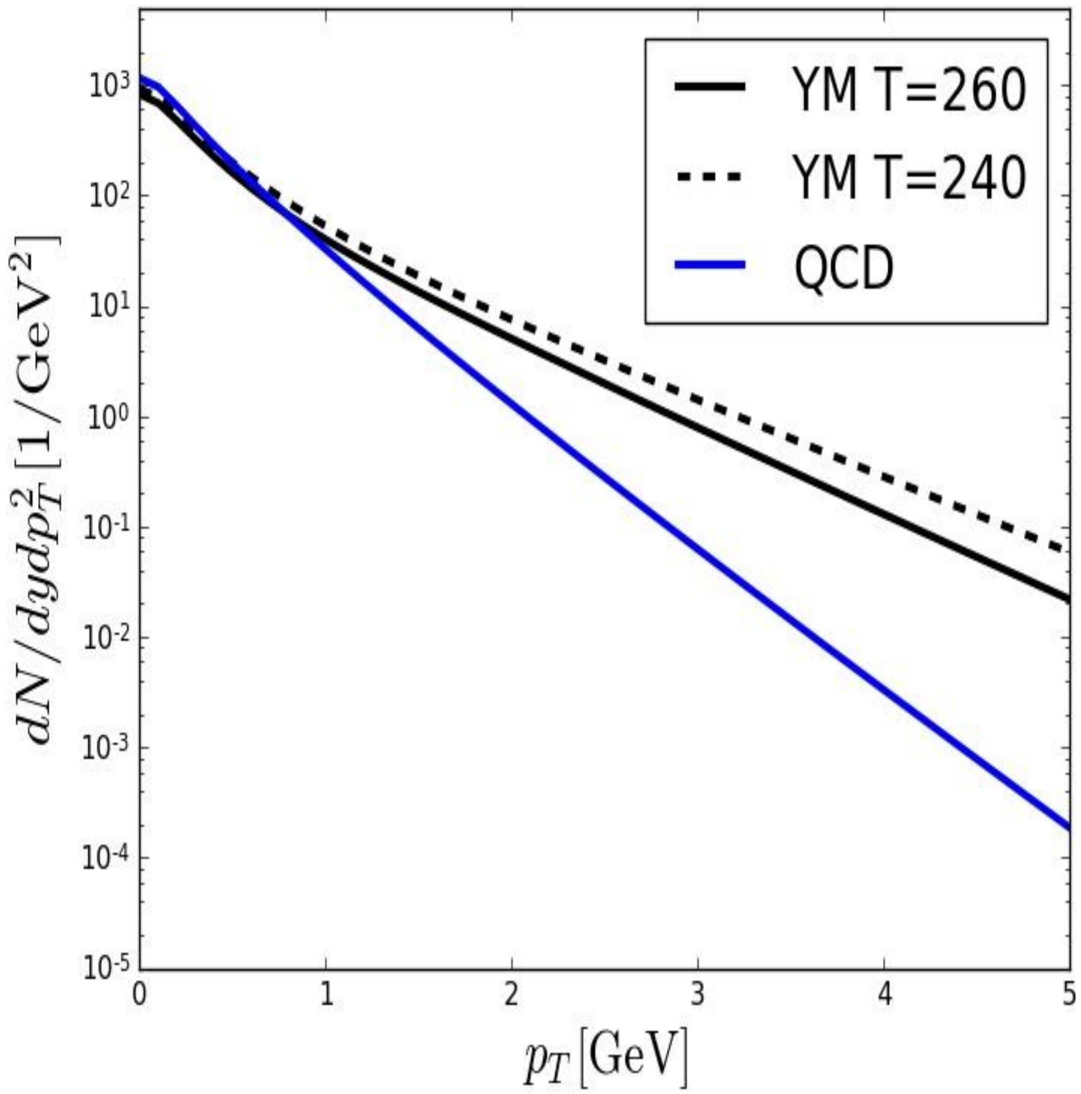
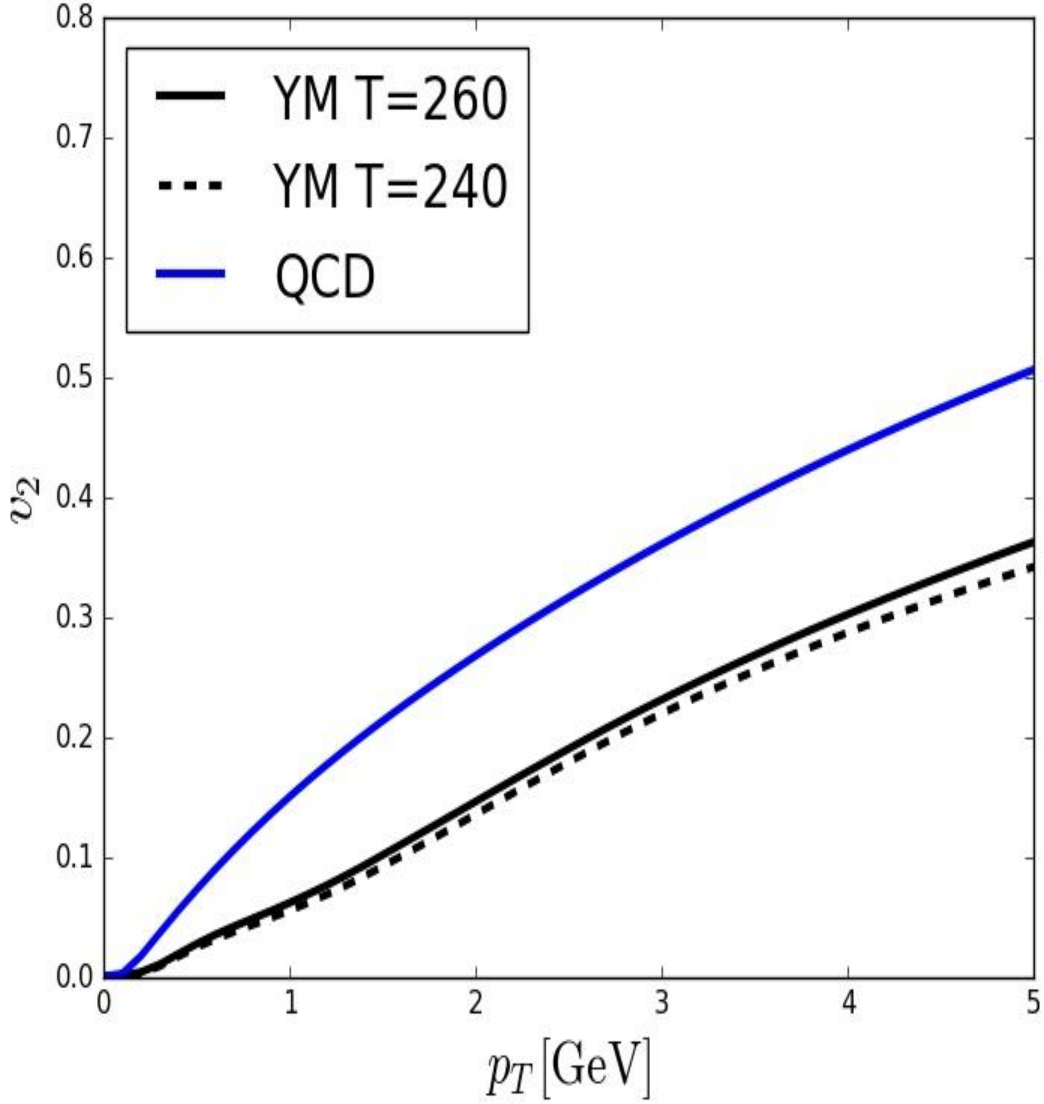


FIG. 12: (Color online) Same as Fig. 11 but for elliptic flow of thermal dileptons.



H. Niemi, LongGang Pang, V. Vovchenko, HST



H. Niemi, LongGang Pang, V. Vovchenko, HST

Identification of Glueballs

Lightest Glueball predicted near two states of same Q.N..

"Over population" Predict 2, see 3 states

Glueballs should decay in a flavor-blind fashion.

$$\pi\pi : K\bar{K} : \eta\eta : \eta'\eta' : \eta\eta' = 3:4:1:1:0$$

Production Mechanisms:

Certain are expected to by **Glue-rich**, others are Glue-poor. Where do you see them?

Proton-antiproton

Central Production

J/ψ decays

Courtesy of Curtis Meyer, Carnegie Mellon, ODU Colloquium

Observation of **Glueballs in pp, pA, AA**

- violent pp (& AA) collisions
- initial state at LHC:
- Color Glass Condensate
- t=0.1fm/c: glue thermalizes
- **pure glue-plasma** created

- Quenched Lattice SU(3)_c :
- **T_c =270MeV**
- glue plasma -> **GlueBall fluid**
- 1. Order Phase Transition

- Expansion to critical point
- **T_cp =240 MeV** t~1-2 fm/c
- **GlueBalls** + Hagedorn States Mix

- more and more quarks produced: **T_c.o. =155MeV** crossover transition

- **Observables** from Columbia plot
- T>T_cp: **Zero e.m. radiati**on
- Measure T~270 MeV Dilepton mass
- T_c: **Flow collapse** as barometer
- T_cp: **Critical Scattering (MG,WG)**,
- Kurtosis , # fluctuations

- T_c ~ 2*T_co =>
- P_t(pp) ~ **2***p_t(AA)

- M_GlueBalls < 2GeV: „**No**“ Baryons
- **p/pi ~ 0** : Yield p+pBar **<<** mesons
- Lightest GlueBall decays:
- - No decays to 2 Omega, no 2 Rho

- Glue Flavor blind !
- **K/pi=1** Yields: Kaons ~ pions

V. Vovchenko & HAST 2015

Alternate Scenario: pure gauge matter in pp, pA – AA ?

Initial Color Glass Condensate → Glasma thermalizes
fast equilibration of Gluons, slow equil. of quarks
high pressure, entropy gluon plasma
→ fast hydrodynamic expansion of gluon plasma.

↓

1. Order Phase Transition at T_c = 270 MeV of flavorless QCD.

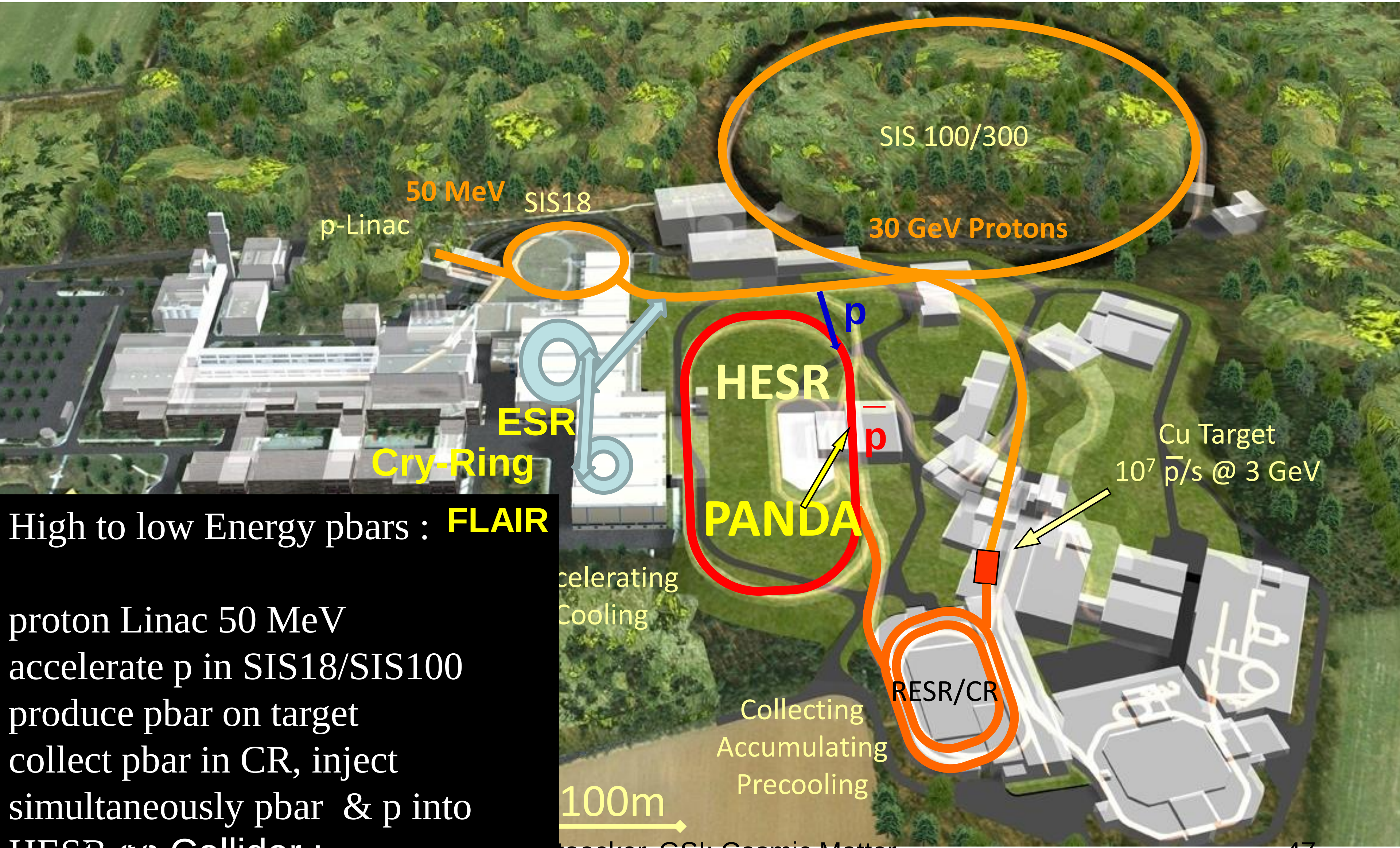
↓

Transition from glue plasma in GlueBall fluid

↓

Glueball-Hagedornstates mix with quarks, decay into Hadrons

Brilliant pbar -p collider L~3*10^30?
Strange, Charm, Beauty matter!

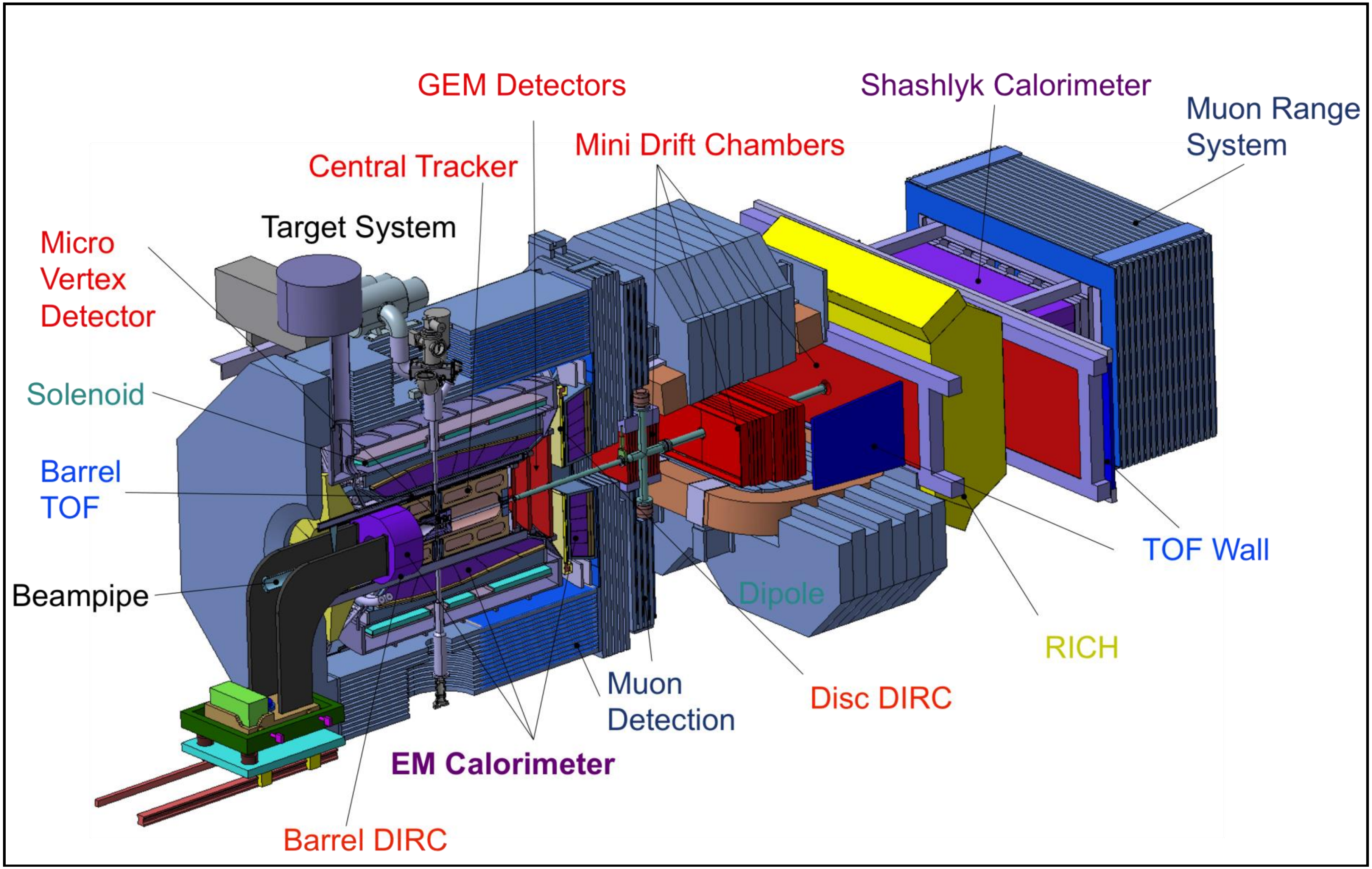


High to low Energy pbars : **FLAIR**

proton Linac 50 MeV
accelerate p in SIS18/SIS100
produce pbar on target
collect pbar in CR, inject
simultaneously pbar & p into
HESR as Collider :
32 GeV pure glue !

Courtesy Jim Ritman,FZJuelich

PANDA Detector



2015

PANDA Program: 2 GeV – 5.5 GeV

I: Hadron spectroscopy

light mesons, baryons, charmonium, open charm,

QCD exotics: **glueballs**, hybrid states, **X,Y,Z**

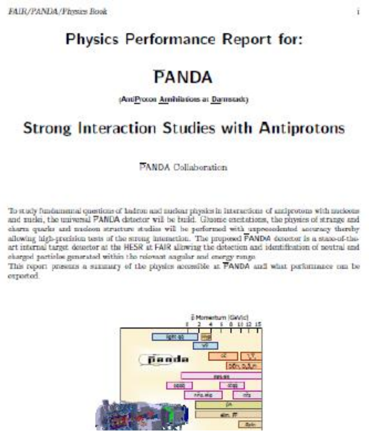
II: Electromagnetic processes

time like form factors, transition distribution amplitudes, TMDs, …

III:Hadronic interactions:

Hyperons, **Hypernuclei**,

In medium-effects



FAIR/PANDA/Physics Book i

Physics Performance Report for:

PANDA

(AntiProton Annihilations at Darmstadt)

Strong Interaction Studies with Antiprotons

PANDA Collaboration

To study fundamental questions of hadron and nuclear physics in interactions of antiprotons with nucleons and nuclei, the universal PANDA detector will be build. Gluonic excitations, the physics of strange and charm quarks and nucleon structure studies will be performed with unprecedented accuracy thereby allowing high-precision tests of the strong interaction. The proposed PANDA detector is a state-of-the-art internal target detector at the HESR at FAIR allowing the detection and identification of neutral and charged particles generated within the relevant angular and energy range.

This report presents a summary of the physics accessible at PANDA and what performance can be expected.

ArXiV:0903.3905

X(3872): PANDA vs. Belle II And BES III

Some numbers, considering J/ψ π⁺π⁻ decay mode only:

- PANDA, assume σ($\bar{p}p \rightarrow$ X(3872))=50 nb
  statistics ~130 (1300) per day on peak for $\mathcal{L}$=2 x 10^{31} (10^{32}) cm^{-2} s^{-1}
  efficiency ~50% (4 charged, exclusive)
  high boost β =0.89 (fixed target) → βγ=1.95
  mass
) measurement
  e X(3872),
  : lineshape!
- Belle
  statis
  effien
  small boost βγ=0.43 (Belle), βγ=0.28 (Belle II)
  mass resolution ~10-20 MeV (unfitted)

350 X(3872)/day
820 Y(4260)/day
176 Z(3900)/day

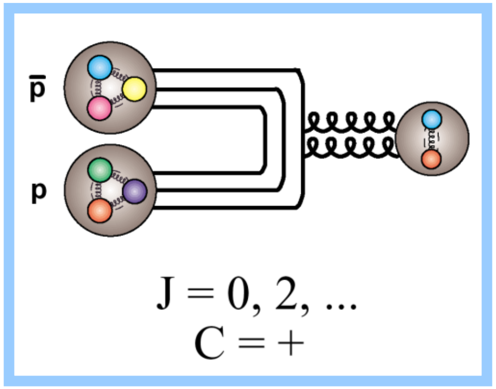
P̄ANDA is an
X Y Z factory

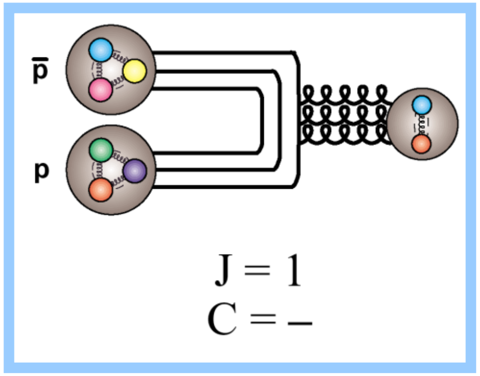
- BESIII
  e+e− → Y(4260) → γX(3872) BESIII, Phys. Rev. Lett. 112(2014)092001
  ≃1200 Y(4260) per day (σ≃60 pb, integrated luminosity ~20 pb^{-1}/day)
  but branching fraction small, only ≃0.5% (≃20 events in ~4 weeks)
  rare

[S.Lange, Worms 2014]

Particle production in $\bar{p}p$ collisions

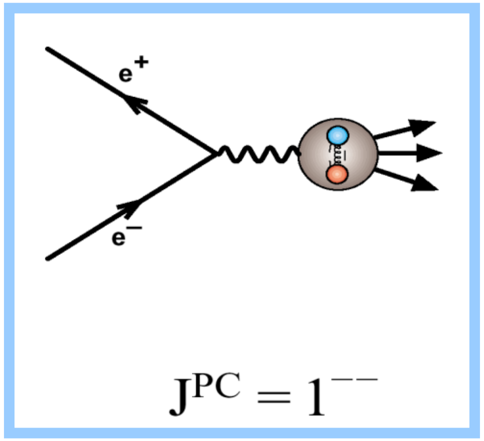
Formation:





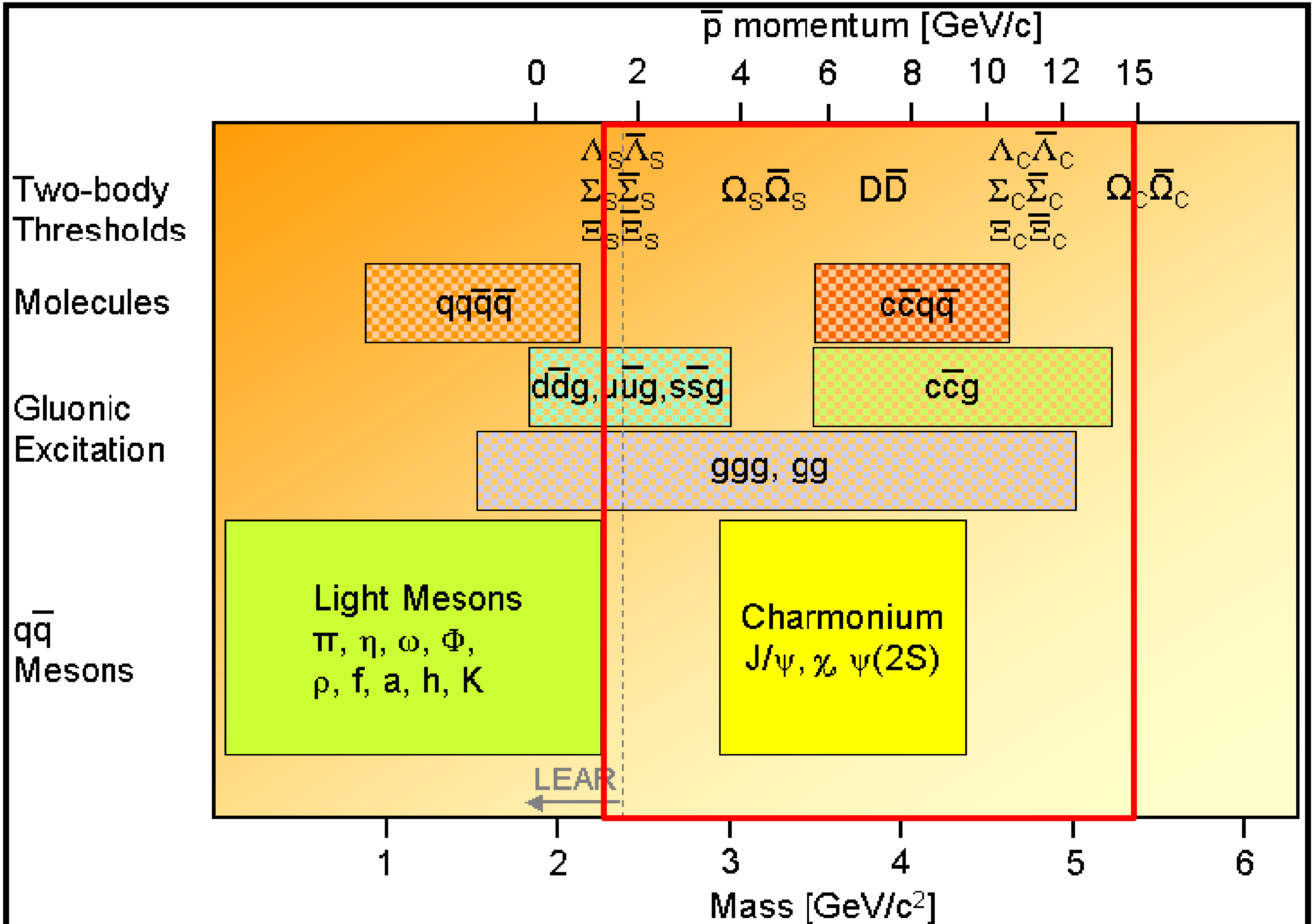
➡ All J^{PC} allowed for $(\bar{q}q)$ accessible in $\bar{p}$ p

c.f.



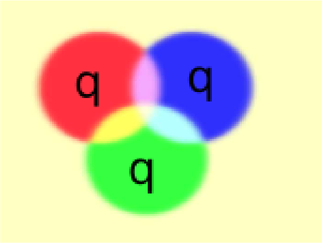
Only $J^{PC} = 1^{--}$ allowed in e^+e^-
(to 1st order)

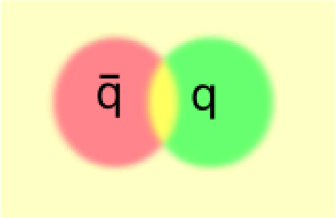
X, Y, Z, Charm-Hybrids, Penta-Quarks, Tetra-quarks, Glue-Balls
- PANDA explores their properties up to masses ~ 5.5 GeV



Beyond standard quark configurations

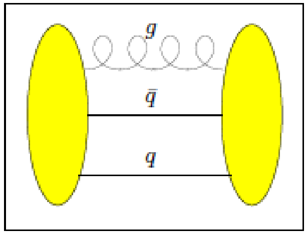
- QCD allows much more than what we have observed:



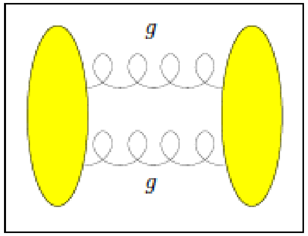


Mesons

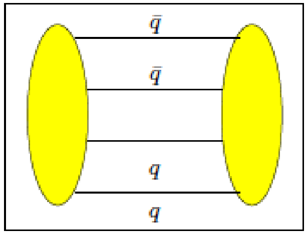
Exotica



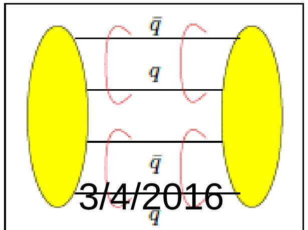
hybrid:
with gluon excitation



glueball:
pure gluon state



4 quark state:
compact 4–quark state



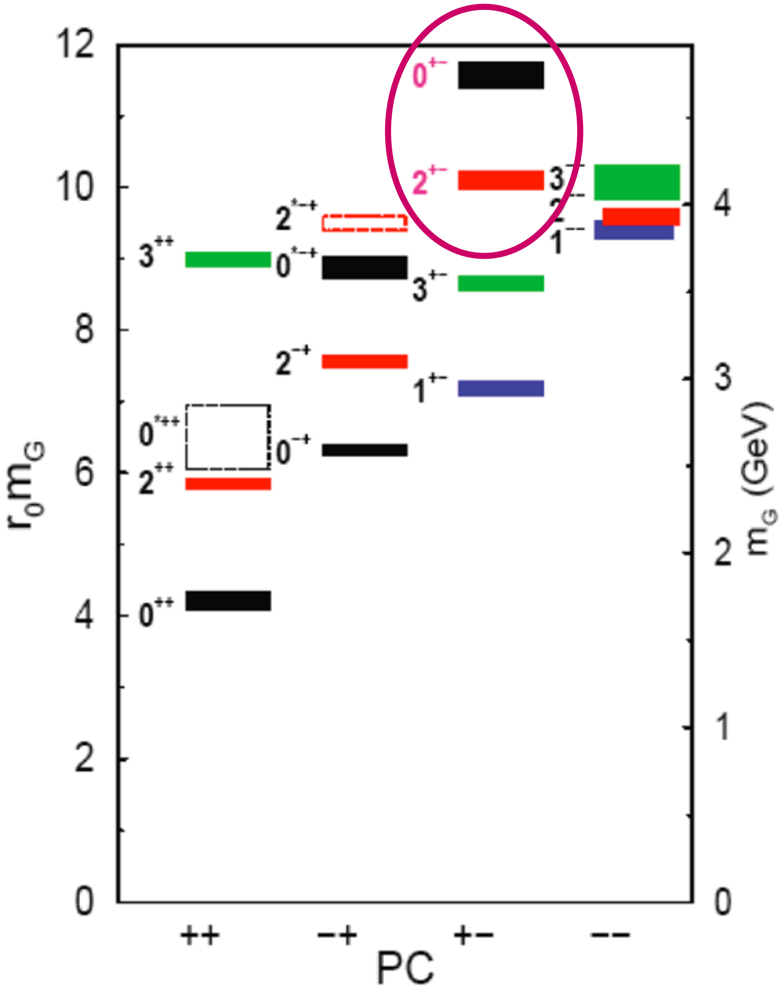
hadronic molecule:
bound state of two mesons

may have J^{PC} not allowed for $q\bar{q}$

Courtesy C. Hanhart

Lattice QCD vs pure YM: glueballs

Search for Heavy Glueballs



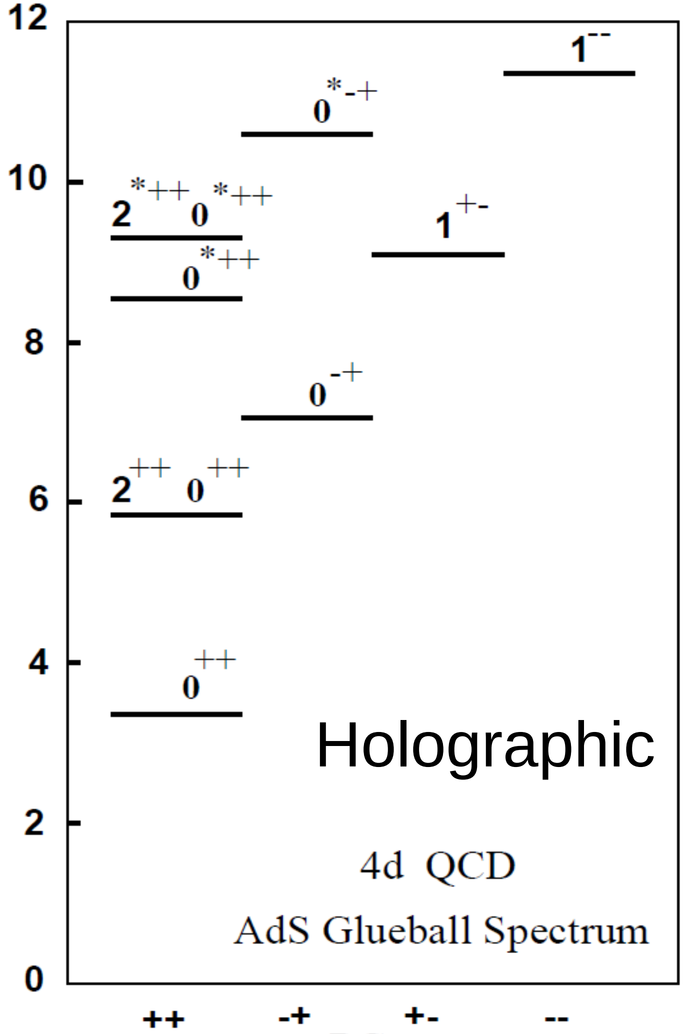
Morningstar & Peardon, PRD60(1999)34509
Morningstar & Peardon, PRD56(1997)4043 **QUENCHED pure gauge** *Lattice theory*

- **Charmed Glueballs**
  - **flavour blind decays**
    - **charmed final states**
  - **only a few charmed mesons around 3 - 4 MeV/c^2**
    - **less mixing**
- **Exotic glueballs (oddballs), no mixing!**
  - **$m(2^{+-}) = 4140(50)(200)$ MeV**
  - **$m(0^{+-}) = 4740(70)(230)$ MeV**
  - **decay modes ϕϕ, ϕη, J/ψη, J/ψϕ**
  - **Narrow widths predicted**

Wuppertal Bcoll., RBRC-Bielefeld coll, Owe Pilipsen, Goethe Uni Frankfurt

Holographic vs. lattice glueball spectra

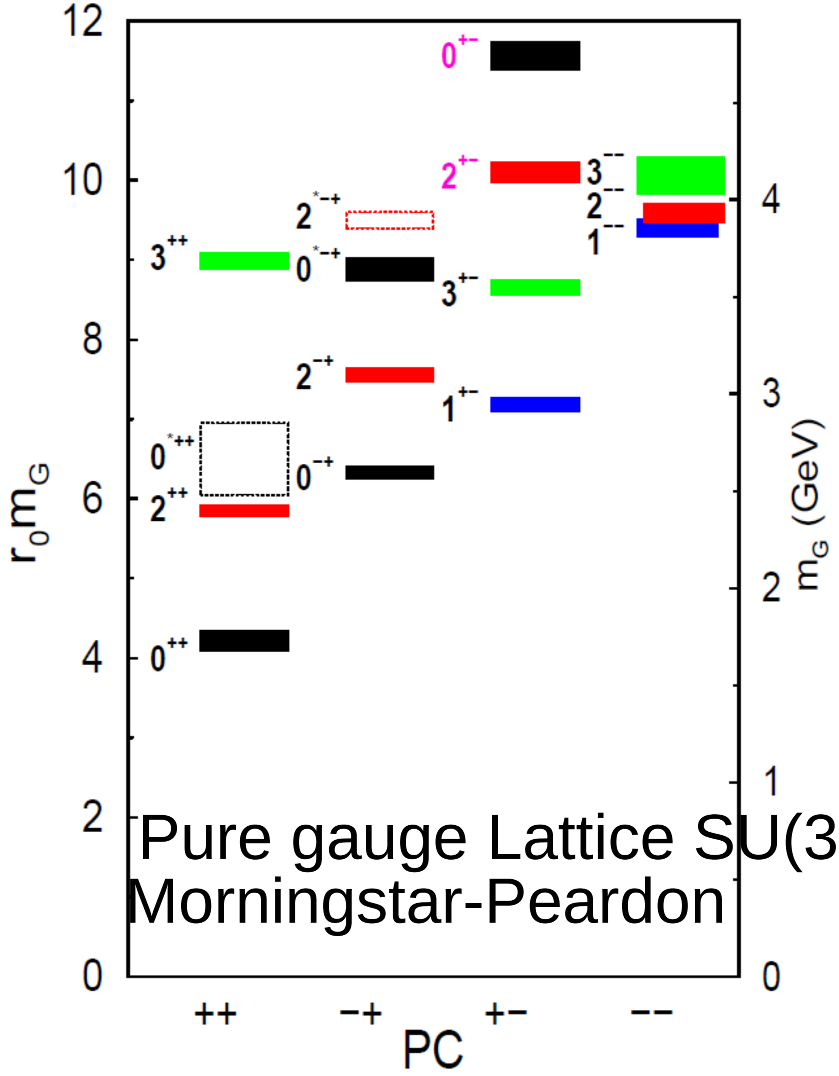
Seiji Terashima,YITP,Kyoto, Koji Hashimoto,Riken, Chung-I Tan,Brown, arXiv:0709.2208



Holographic

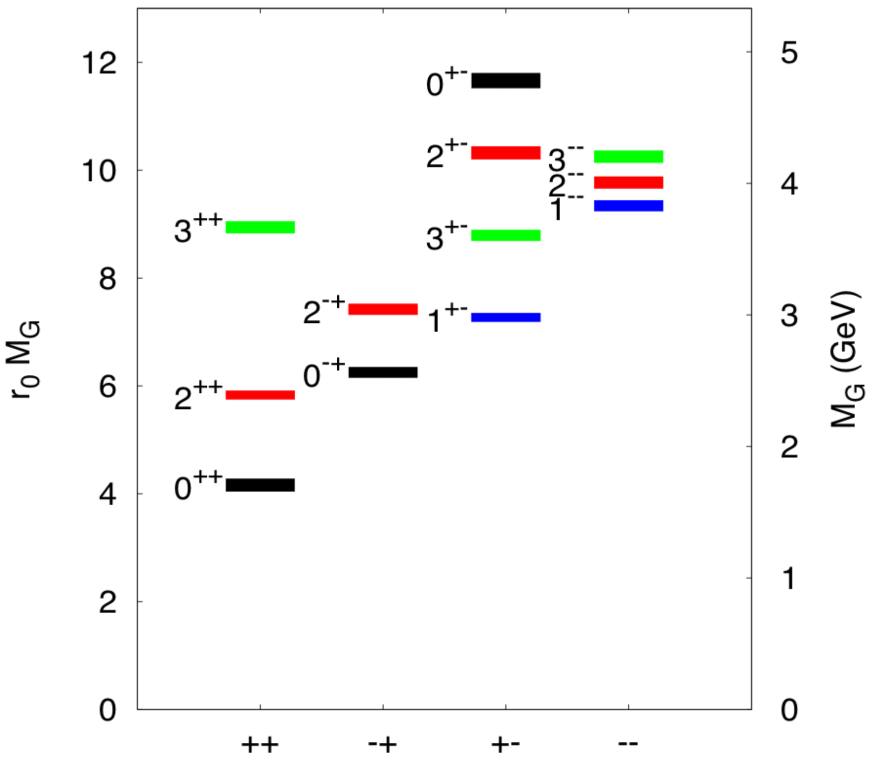
Brower-Mathur-Tan, 2000

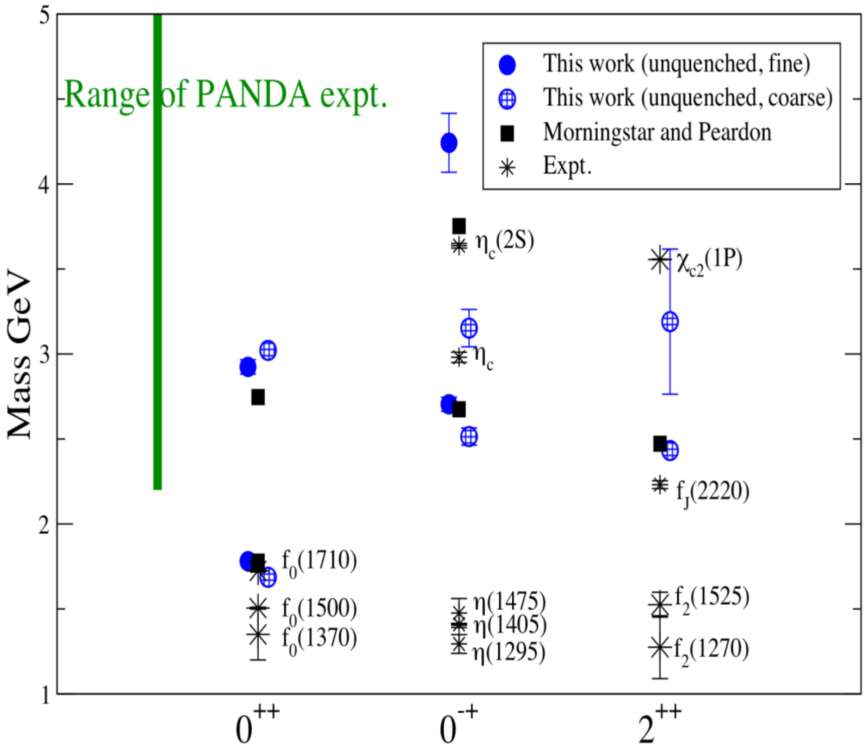
$P_\tau = -1$ dropped



Pure gauge Lattice SU(3)
Morningstar-Peardon

Glueball spectrum





Quenched results:
Morningstar-Peardon
Phys.Rev. D73 014516 (‘06)

First unquenched results:
pion mass 360 MeV
UKQCD coll. PRD82 (‘10) 34501

Pure YM gauge theory on the lattice:

a hot glue plasma

a 1. Order PhaseTransition,

a warm Glueball Fluid ! ?

The early eighties: predictions of QCD phase structure

1. two different phase transitions:

Svetitsky&Yaffe**: F.O.P.T. in pure gauge YM theory:**

"glueplasma – GlueBall fluid" – no quarks!

Pisarski&Wilczek**: chiral massless quarks**

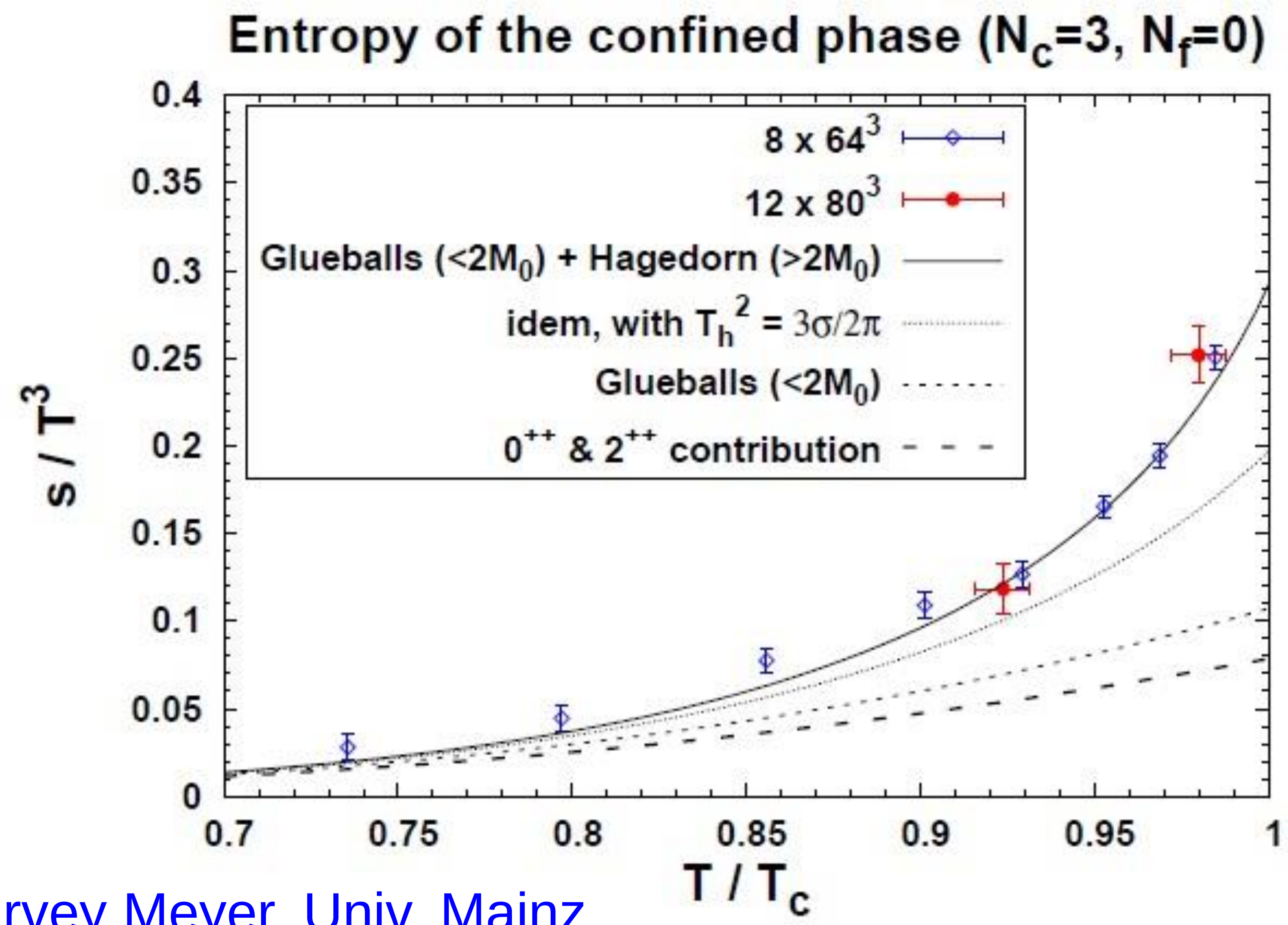
F.O.PT QGP-Hadrons, but crossing if quark mass nonzero

2. - two chemical saturation eq. timescales in RHICs:

Raha/Sinha; Shuryak; T. Biro, B. Mueller, X.Y. Wang **Transport Theory**
Fast chemical saturation: pure glue! But Slow saturation: quarks !

Search for pure gauge YM F.O.P.T. at early times in colliders?
=> Early pp, pA: **Glue <=> GlueBall**: n**ew QCD phase structure?**

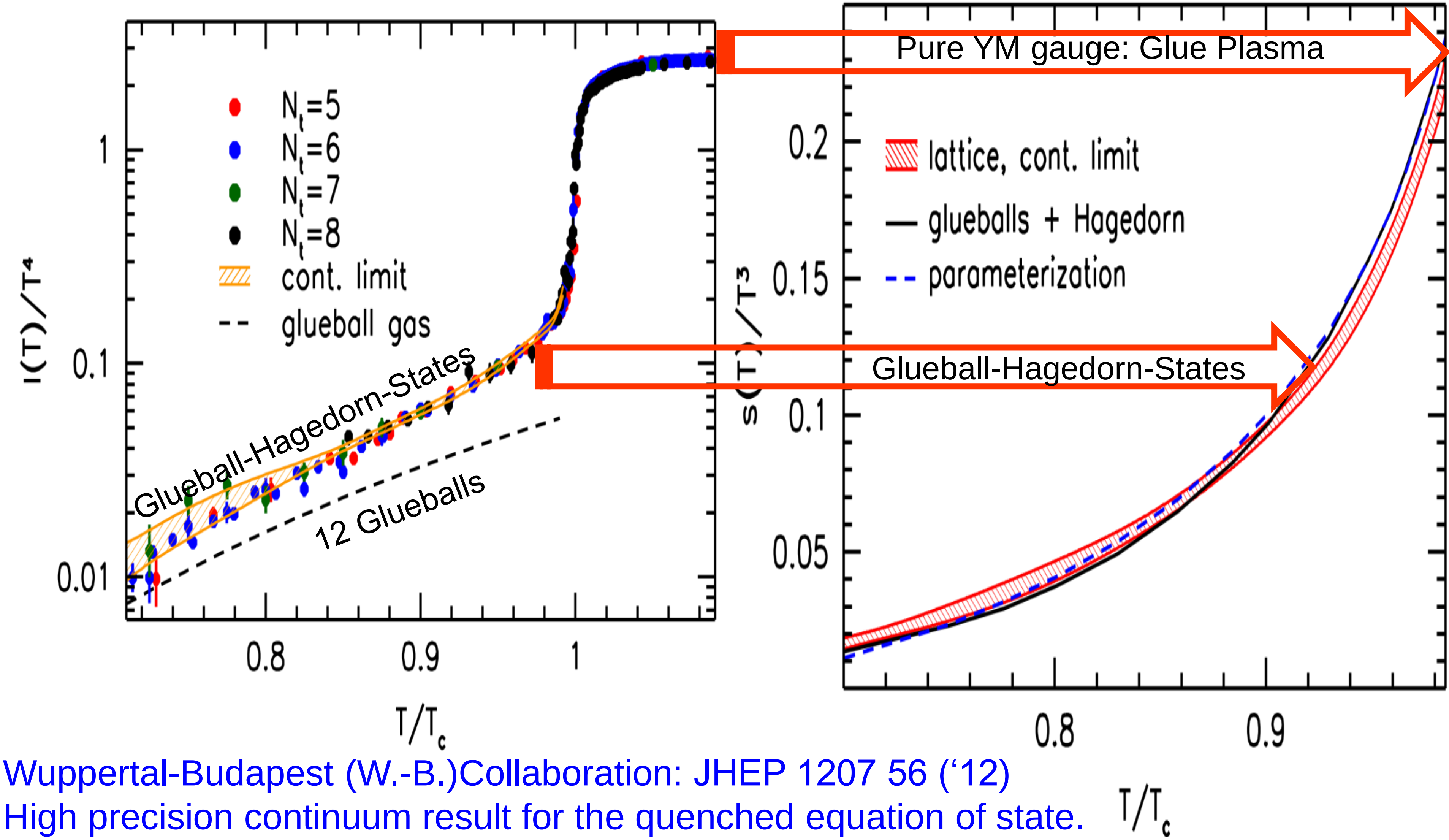
Pure LGT thermal GlueBall-matter observed at RHIC and LHC !?



Harvey Meyer, Univ. Mainz

FIG. 3: The entropy density in units of T^3 for $LT = 8$. We applied a (modest) volume-correction to the $N_t = 12$ data.

Lattice Gauge Thermodynamics of the GlueBall-matter fluid



Pure YM gauge: Glue Plasma

Glueball-Hagedorn-States

Glueball-Hagedorn-States

12 Glueballs

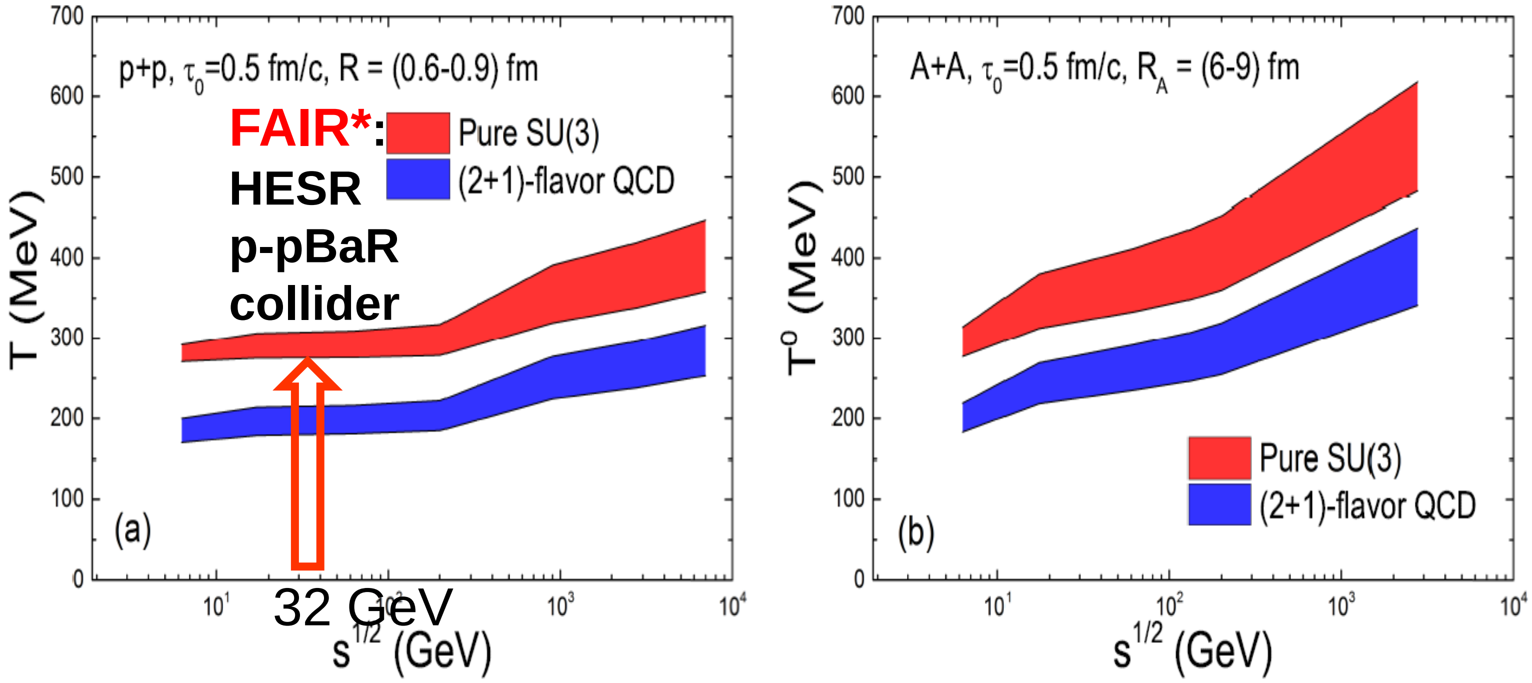
Wuppertal-Budapest (W.-B.)Collaboration: JHEP 1207 56 (‘12)

High precision continuum result for the quenched equation of state.

Low temperature behavior and phase transition described by Hagedorn-GlueBall spectrun

W.-B. use 12 **GlueBall** states (Morningstar-Peardon) plus **Hagedorn-GB** towers

(as proposed by Harvey Meyer).



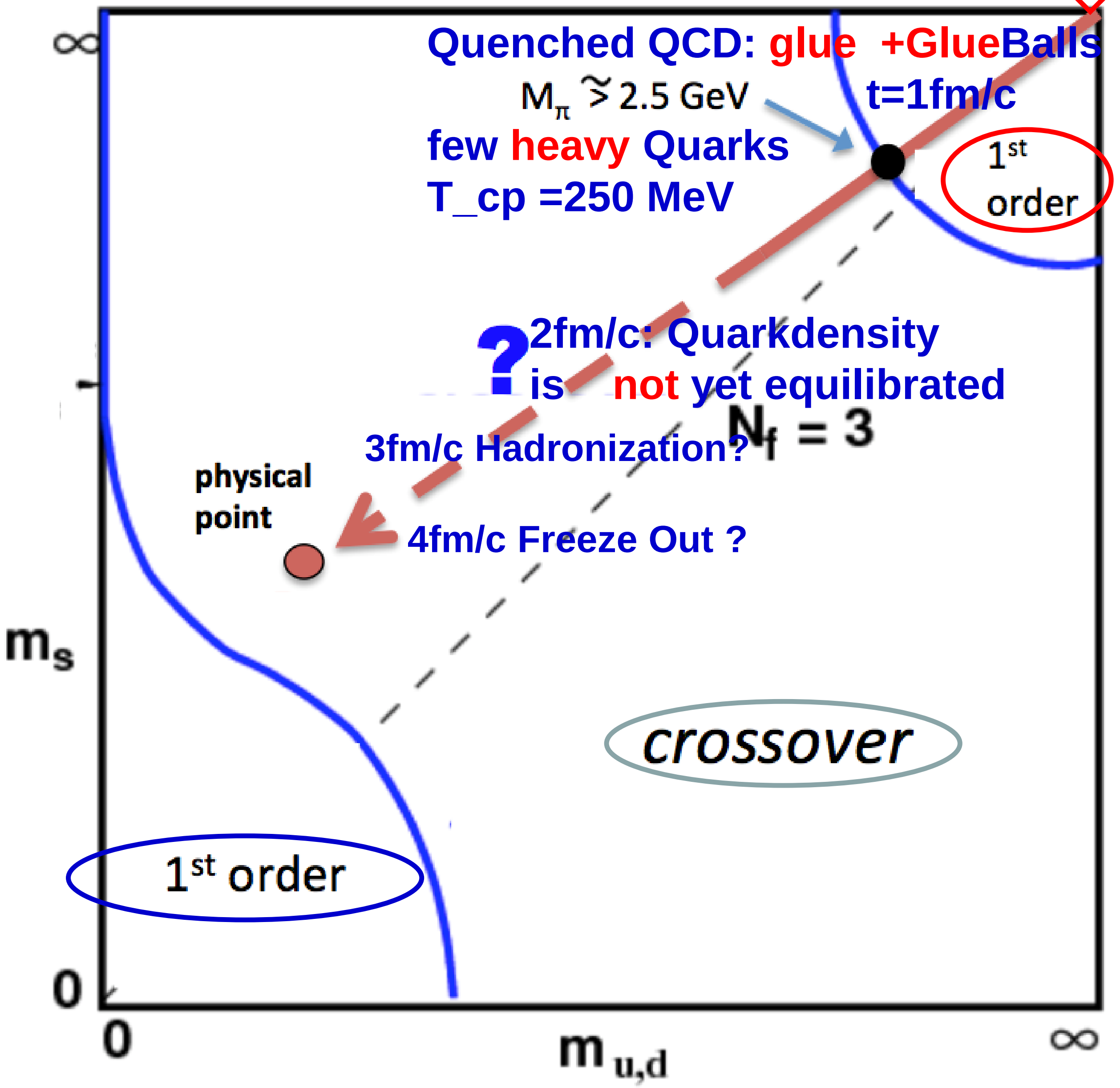
FAIR*: **HESR p-pBaR collider**

32 GeV

FIG. 6: (Color online) Dependence of the initial temperature T^0 on the collision energy for QGP and pure SU(3) scenarios in (a) p+p and (b) $A + A$ collisions. The uncertainty bands result from variation of the transverse radius.

LHC/RHIC/FAiR*: time evol. in pp & AA

pure gauge: glue only!
t=0.1fm/c : No Quarks !



Quenched QCD: glue +GlueBalls

t=1fm/c

few heavy Quarks

T_cp =250 MeV

?2fm/c: Quarkdensity is not yet equilibrated

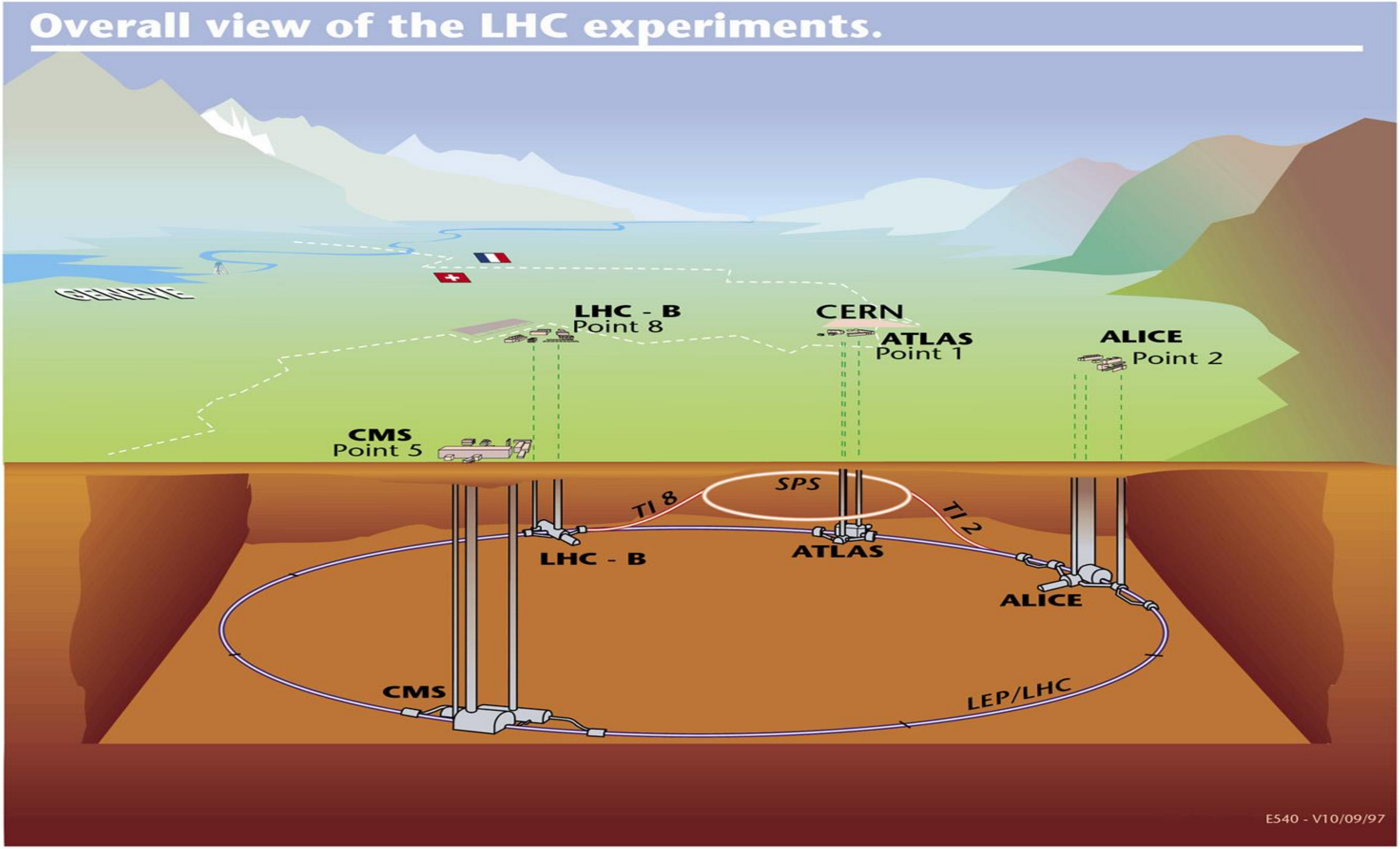
3fm/c Hadronization?

4fm/c Freeze Out ?

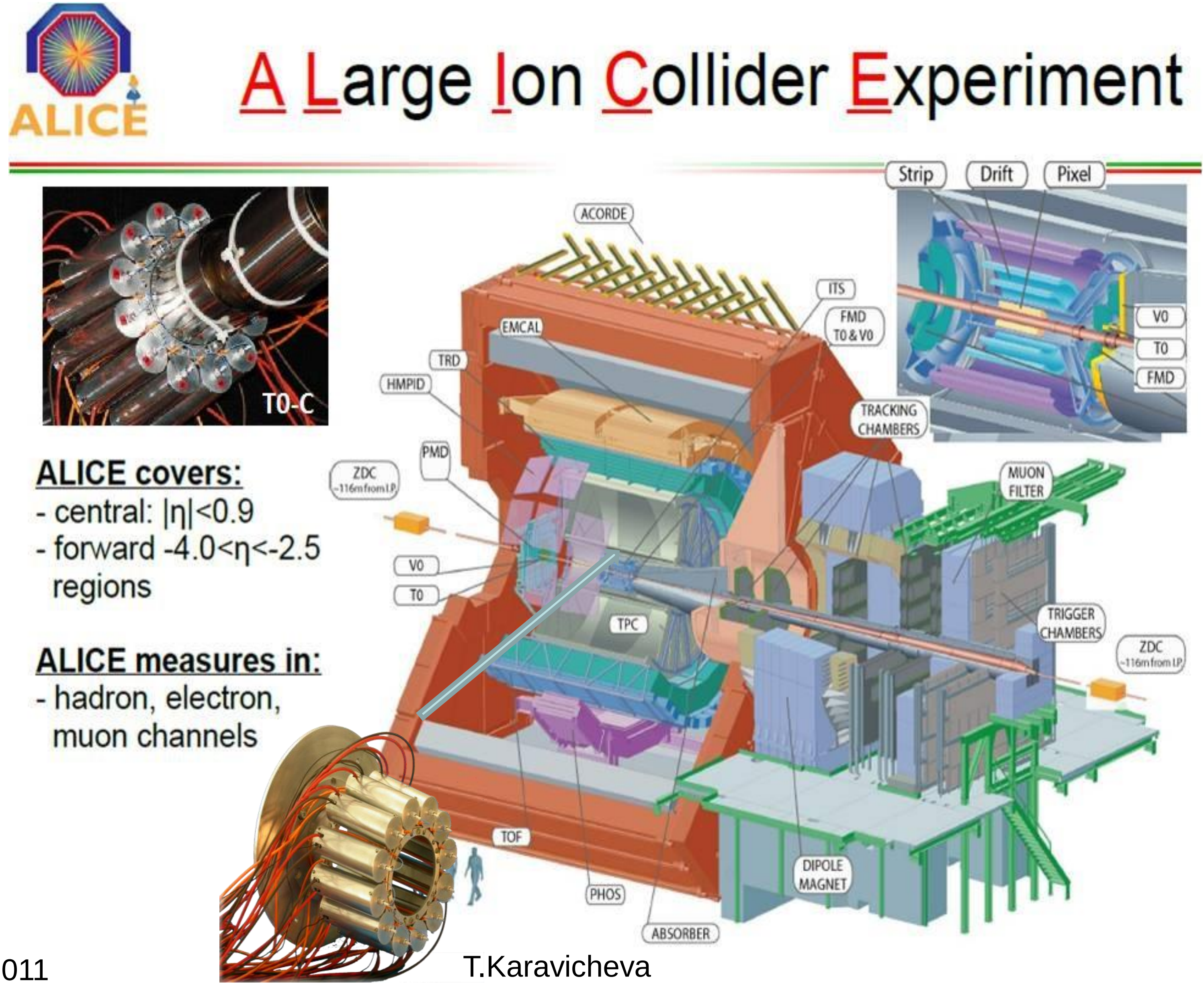
SU(3)_color Lattice Gauge Theory

Columbia Plot: Order of Phase Transitions

Cosmic **GlueBall-Matter** at CERN LHC and BNL RHIC



Cosmic **GlueBall-Matter** at CERN LHC and BNL RHIC



ALICE

A Large Ion Collider Experiment

ALICE covers:
- central: |η|<0.9
- forward -4.0<η<-2.5 regions

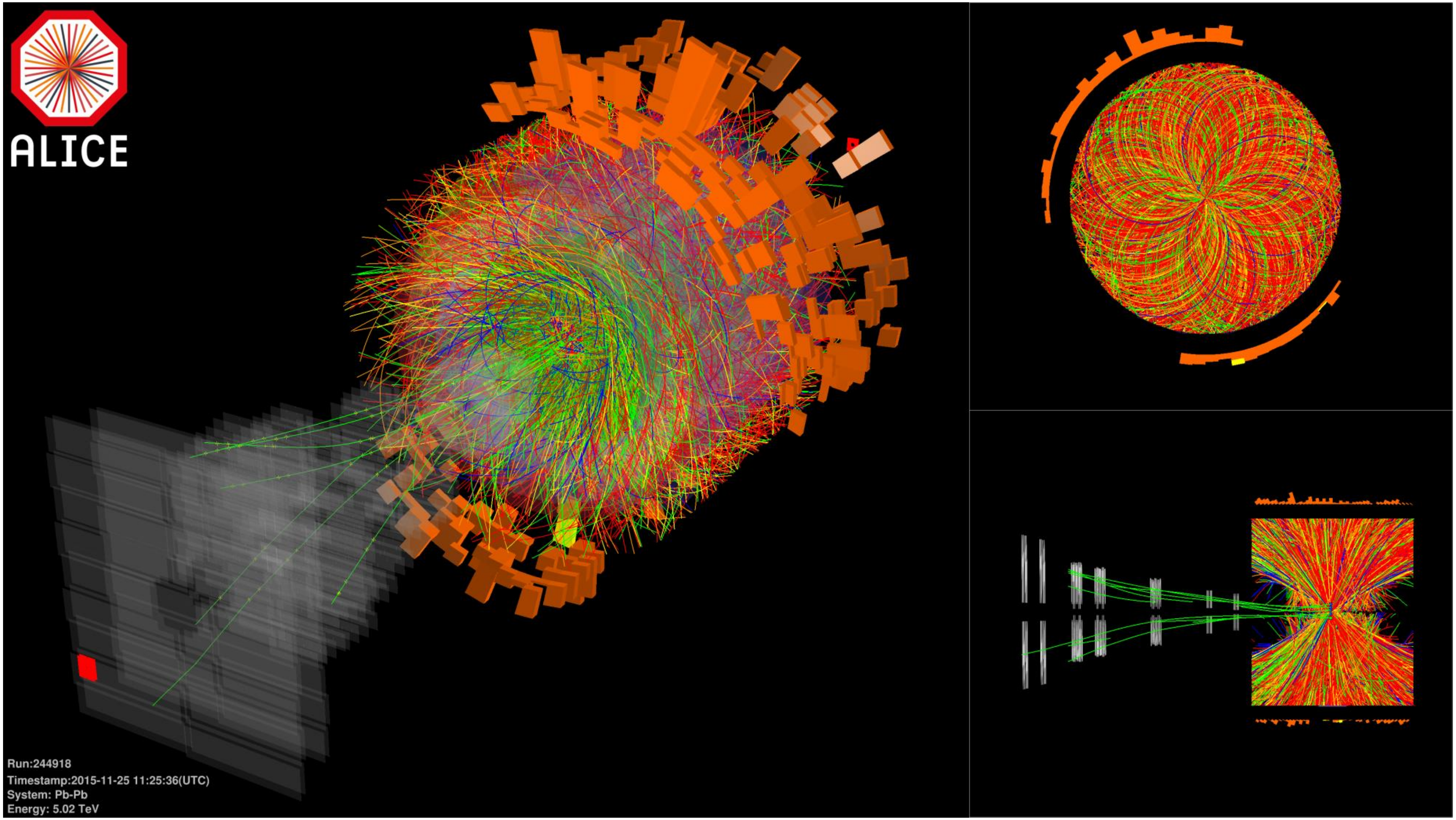
ALICE measures in:
- hadron, electron, muon channels

ALICE @ LHC: Pb-Pb collisions $\sqrt{s_{NN}} = 5.02$ TeV

First Data Nov. 25

LHC design HI luminosity 10^{27} $s^{-1}cm^{-2}$ Dec. 1

Increase of statistics by a factor of 3-10 (centrality, ...)



Extreme computing challenges require power efficient high performance computing data storage & -analysis: Spin-off from Nuclear Physics to Industry & Business

Green Cube at GSI -4- FAIR

Nr.1 Green-500: GSI L-CSC Computer
Supercomputer Fair, New Orleans, USA
November 2014

12 MW power consumption, PUE<1.07
T. Kollegger, AIME Big Data, Budapest

5.27 Gflops/watt power consumption
with AMD FirePro GPU

Traditional picture of QCD matter in Heavy Ion Collisions

Initial Color Glass Condensate → Glasma thermalizes
→ fast equilibration of Gluons and Light flavor quarks
high pressure, entropy → hydrodynamic expansion
→ flow v2 as excellent Barometer: probe of QCD matter.

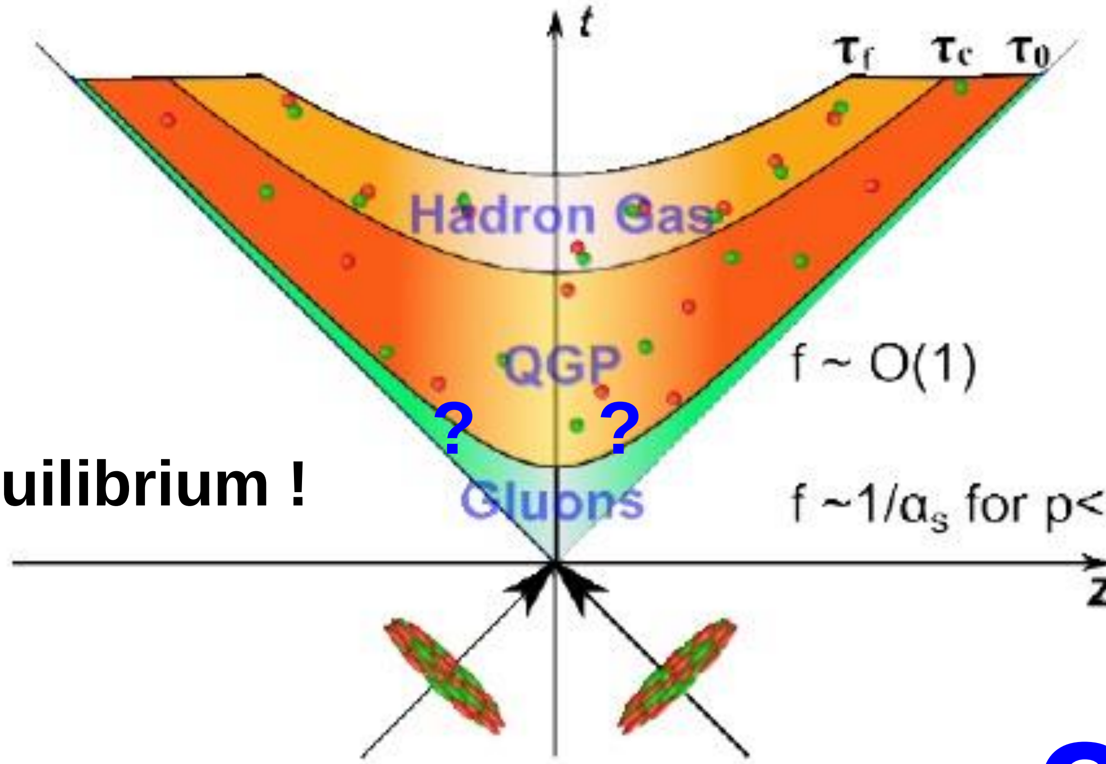
Hadronization @ T=155MeV: crossing of 2+1 flavor QCD

Hadronic yields and v2 at RHIC and LHC measured=> FIT !

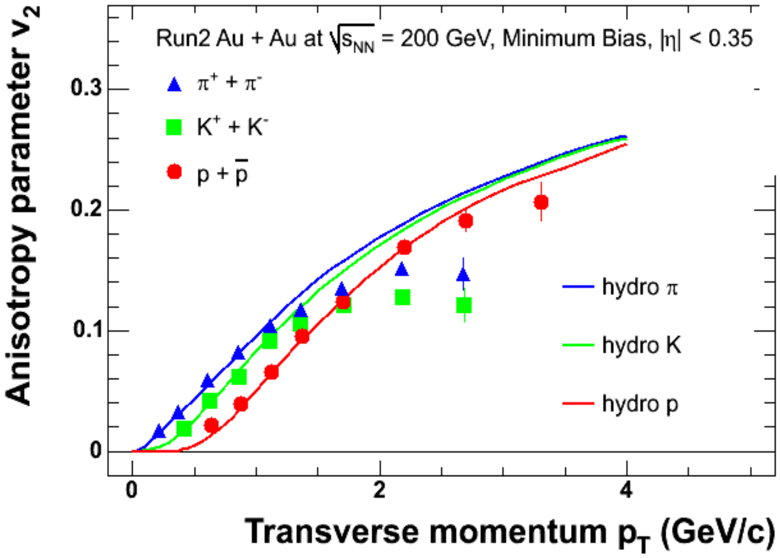
Comparison of v2, HRG T= 155 MeV, with LHC data
“understanding” of QCD matter and - dynamics

Fast thermalization required for Hydro

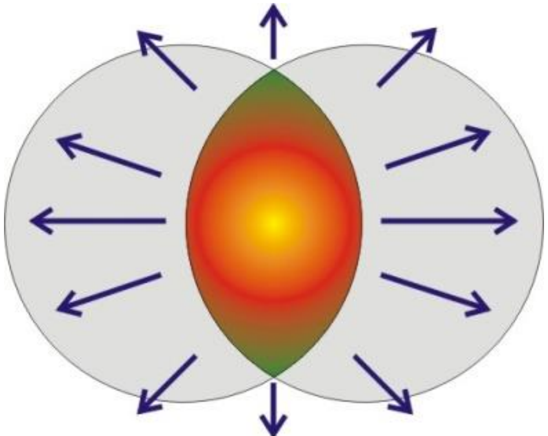
how can a system evolve to thermal equilibrium in such a very short time?

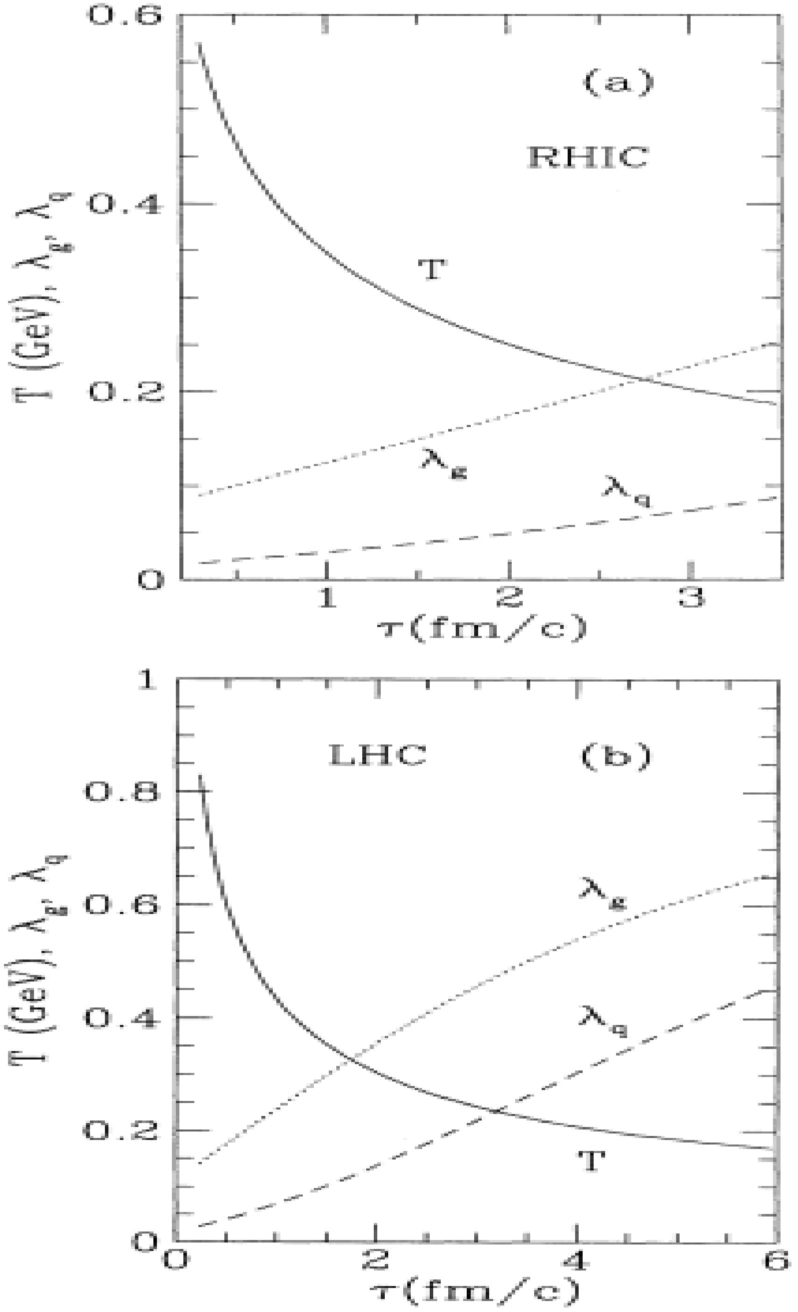


Initially: very far from equilibrium !



2+1QCD Hydro-Onset time < 1fm/c ?





But:

Time evolution of fugacity

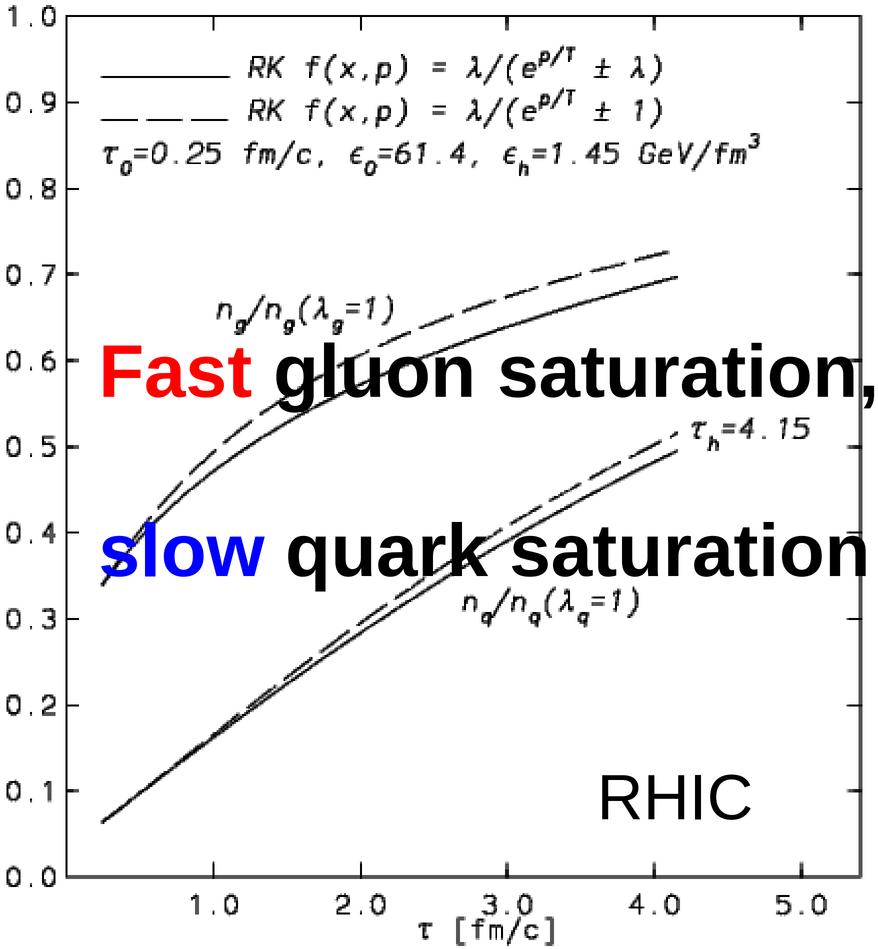
$$fugacity = n / n^{eq}$$

of gluons and quarks (g, q) from pQCD-based rate eq.

Fast gluon saturation,

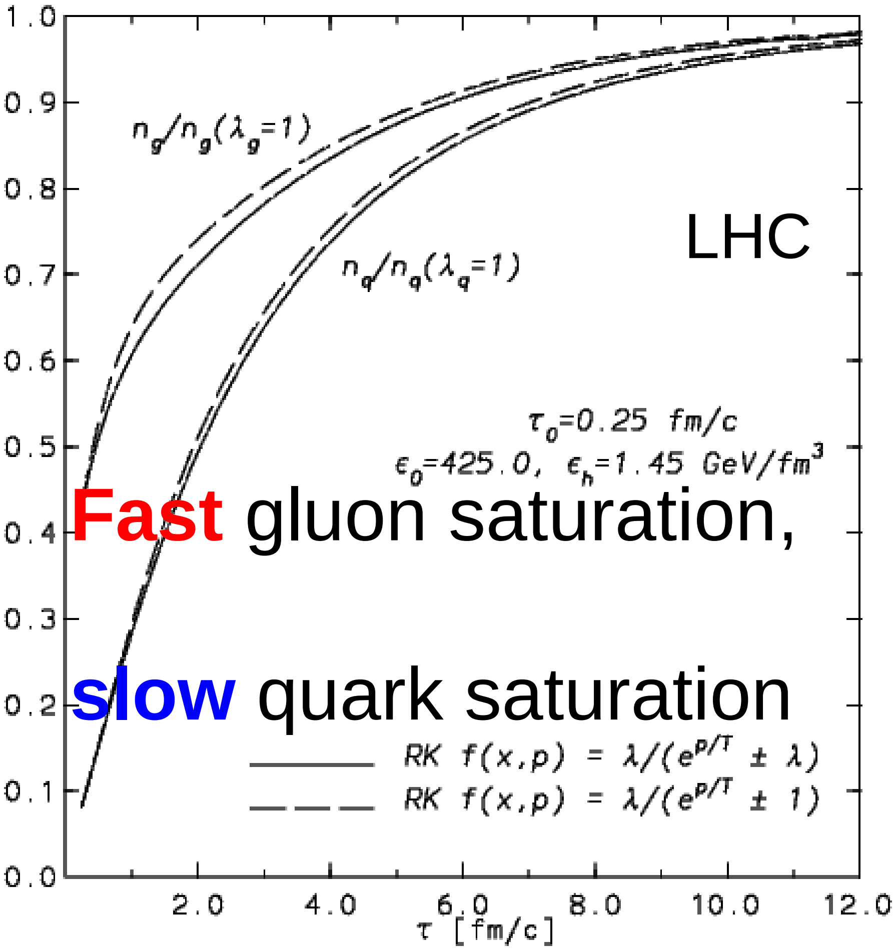
slow quark saturation

T. S. Biró, B. Mueller, X. N. Wang,
BMW-coll. , PRC48,1275 (1993)
also Kaempfer et al,
also Strickland...



Fast gluon saturation,

slow quark saturation



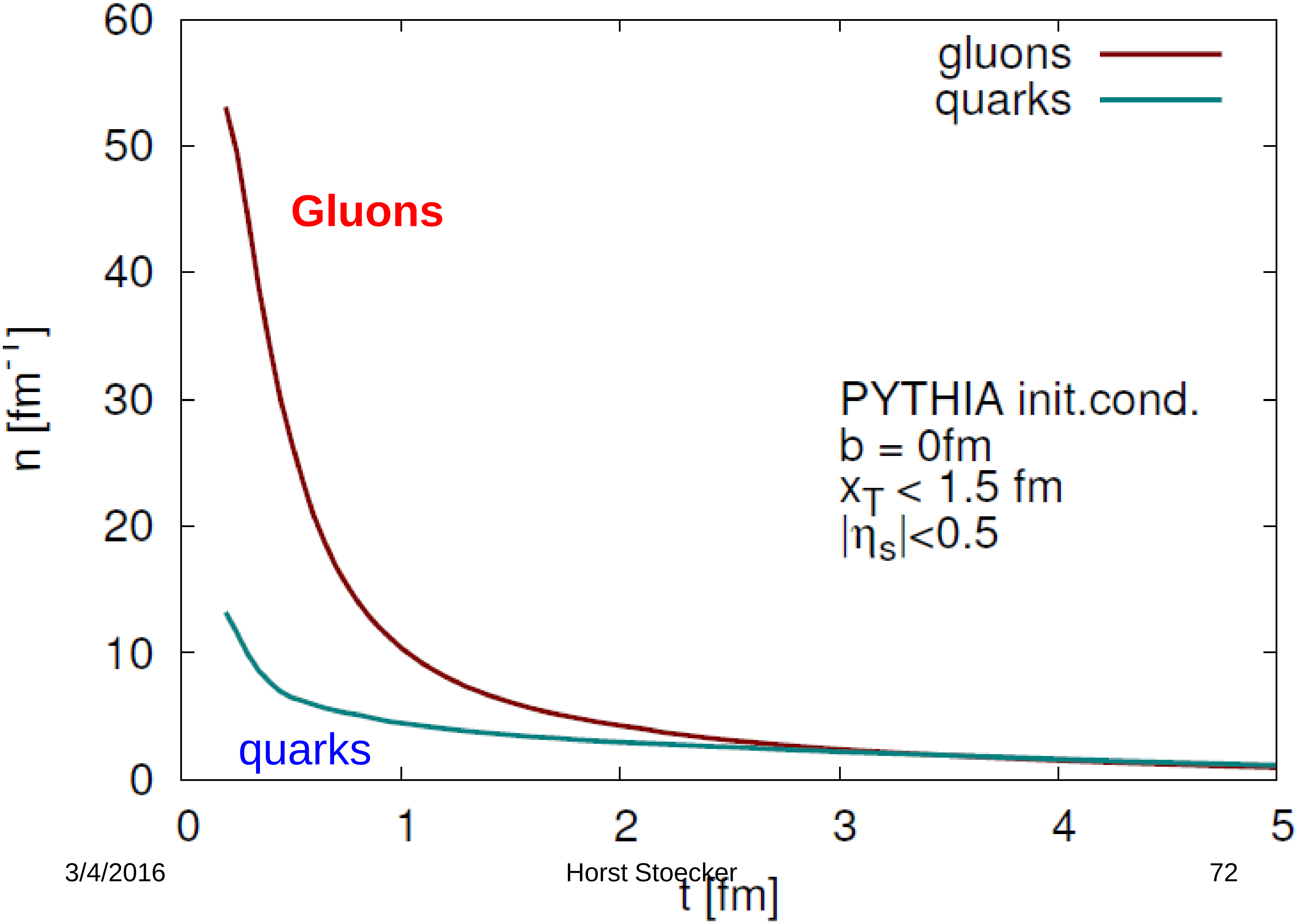
Fast gluon saturation,

slow quark saturation

Rate equation calculation

D.M. Elliott, D.H. Rischke,Nucl.Phys. A671,583 (2000)

Gluon yields & quark yields F. Senzel, Z. Xu, C. Greiner BAMPS



Pure YM Glue Matter created at FAIR*, RHIC, LHC ?

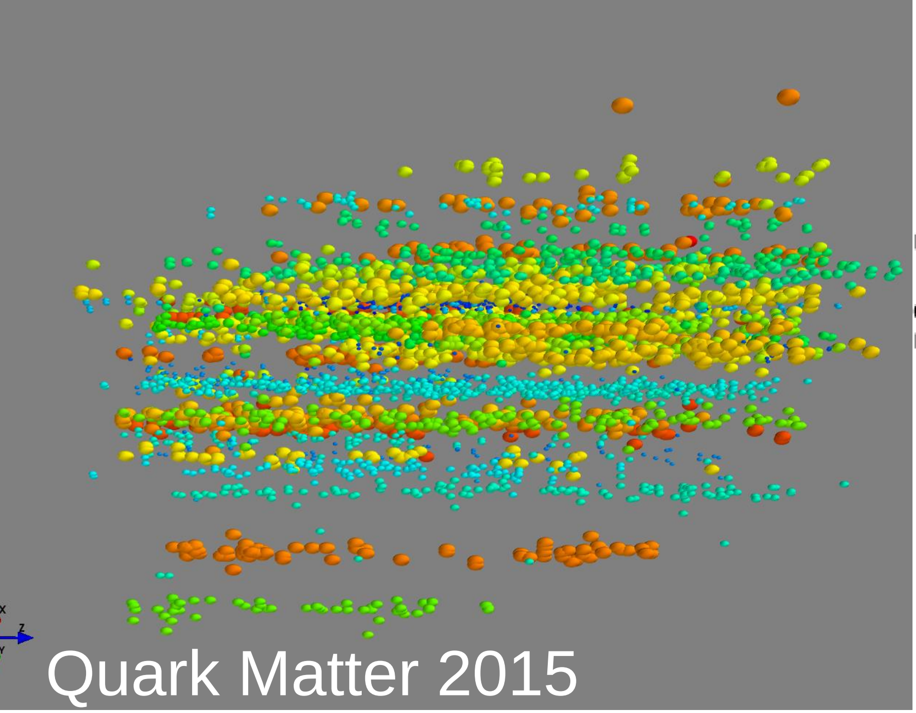
Early proposals for **two** phase transitions and **two timescales** in RHICs:

Svetitsky Yaffe Pisarski Wilczek Raha Sinha Shuryak Biro Kaempfer

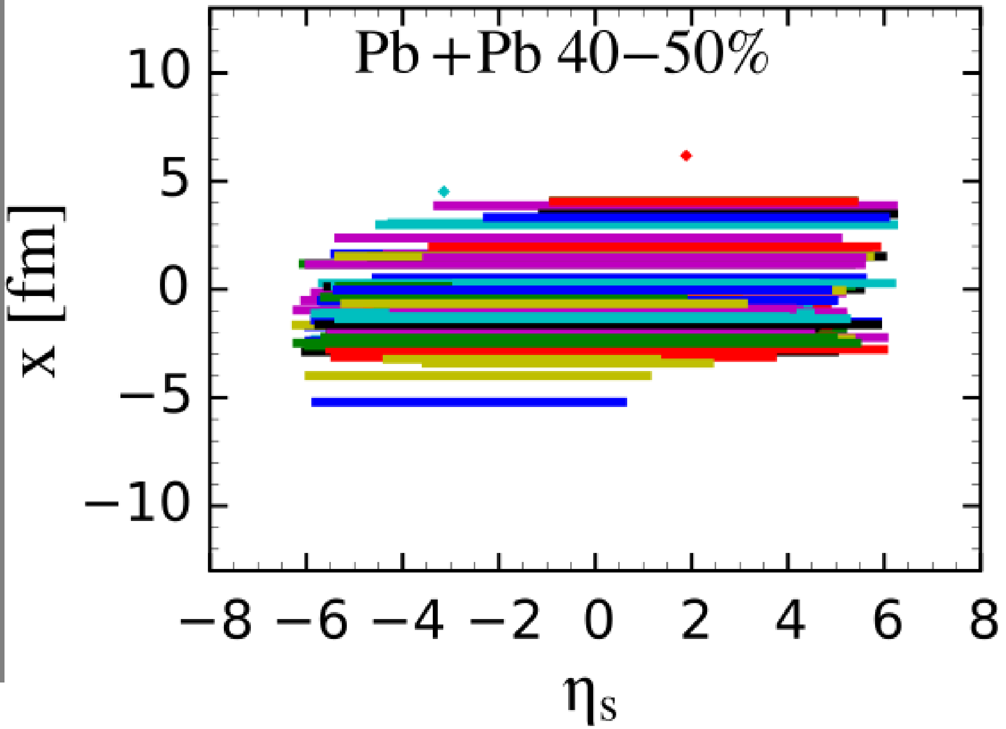
1. **CGC** Gluon Supersaturation – Overoccupied Glue, BEC
2. **Fast** Gluon Equilibration – **slow** quark saturation
3. **Early** 1.Order Phase Trans. in **Yang-Mills gauge** theory
4. **Pure** YM Gaugetheory **N_f =0 -**“physical” **N_f=2+1** QCD **N_f=fct of time**
5. **Second** Transition Quarks-Hadrons 2+1-QuarkGluonPlasma”**crossing”**
6. **GlueBalls-**HagedornStates, two body sequential **decay cascade**
7. **Hadron** yields**, <pt>** vs. Multiplicity, Flow & **Ridge** in pp, pA, AA
8. **Dileptons**, Photons vs. Multiplicity in pp, pA, AA

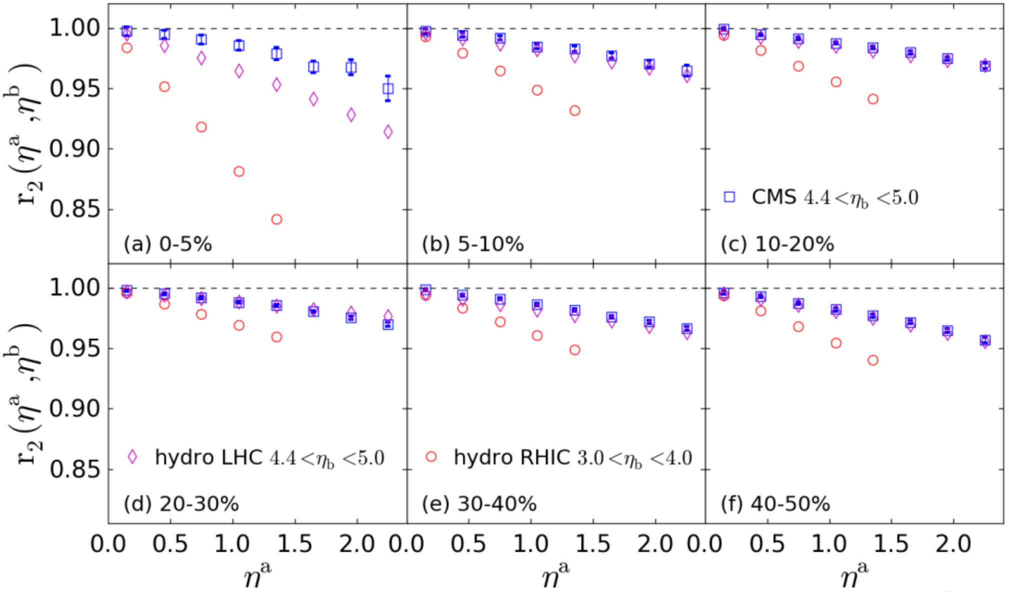
Horst Stoecker, Judah M. Eisenberg Prof., ITP & FIAS, Goethe Univ. Frankfurt

Time evolution of high multiplicity pp AA at RHIC and LHC in pure YM scenario



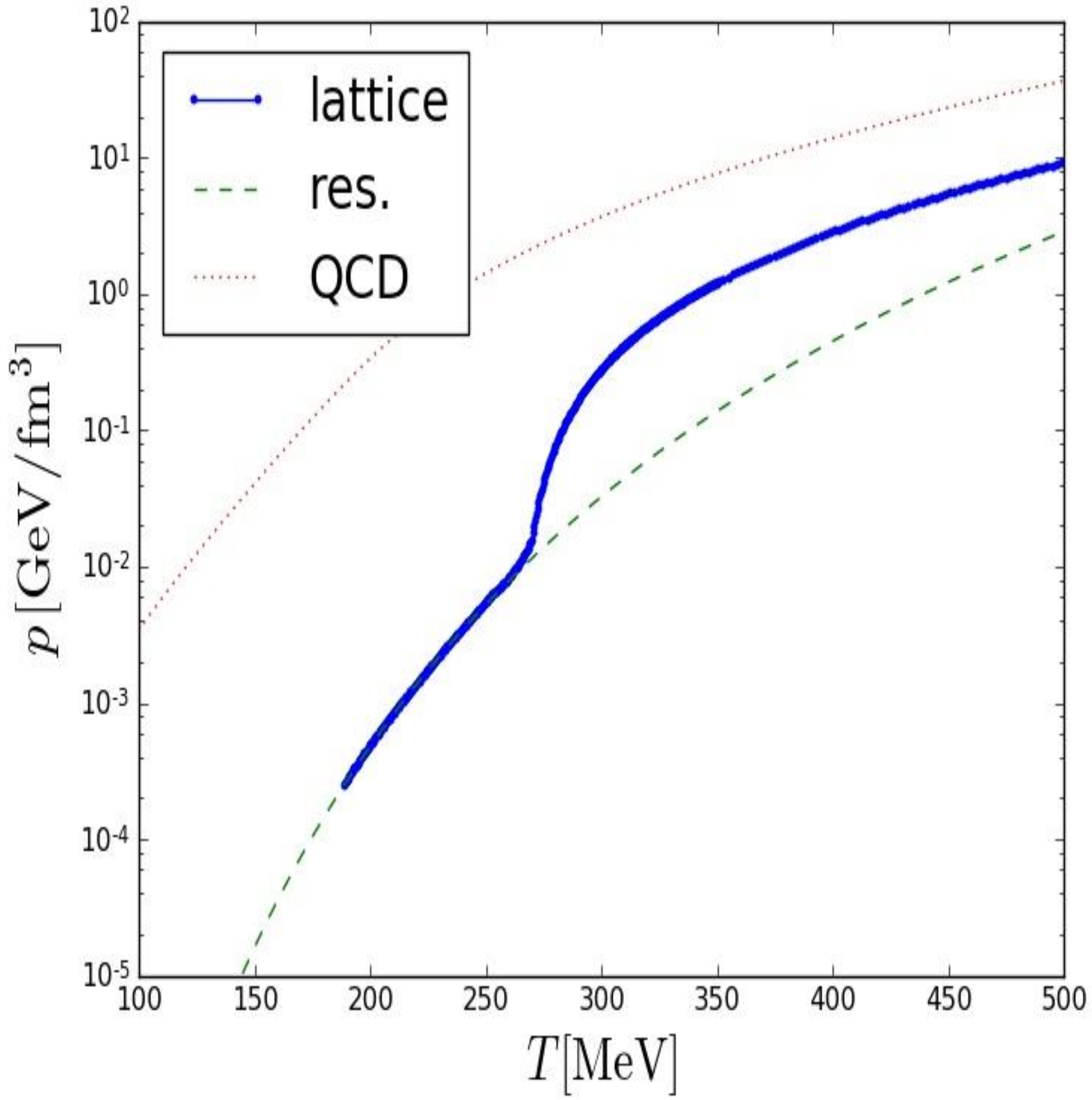
Quark Matter 2015



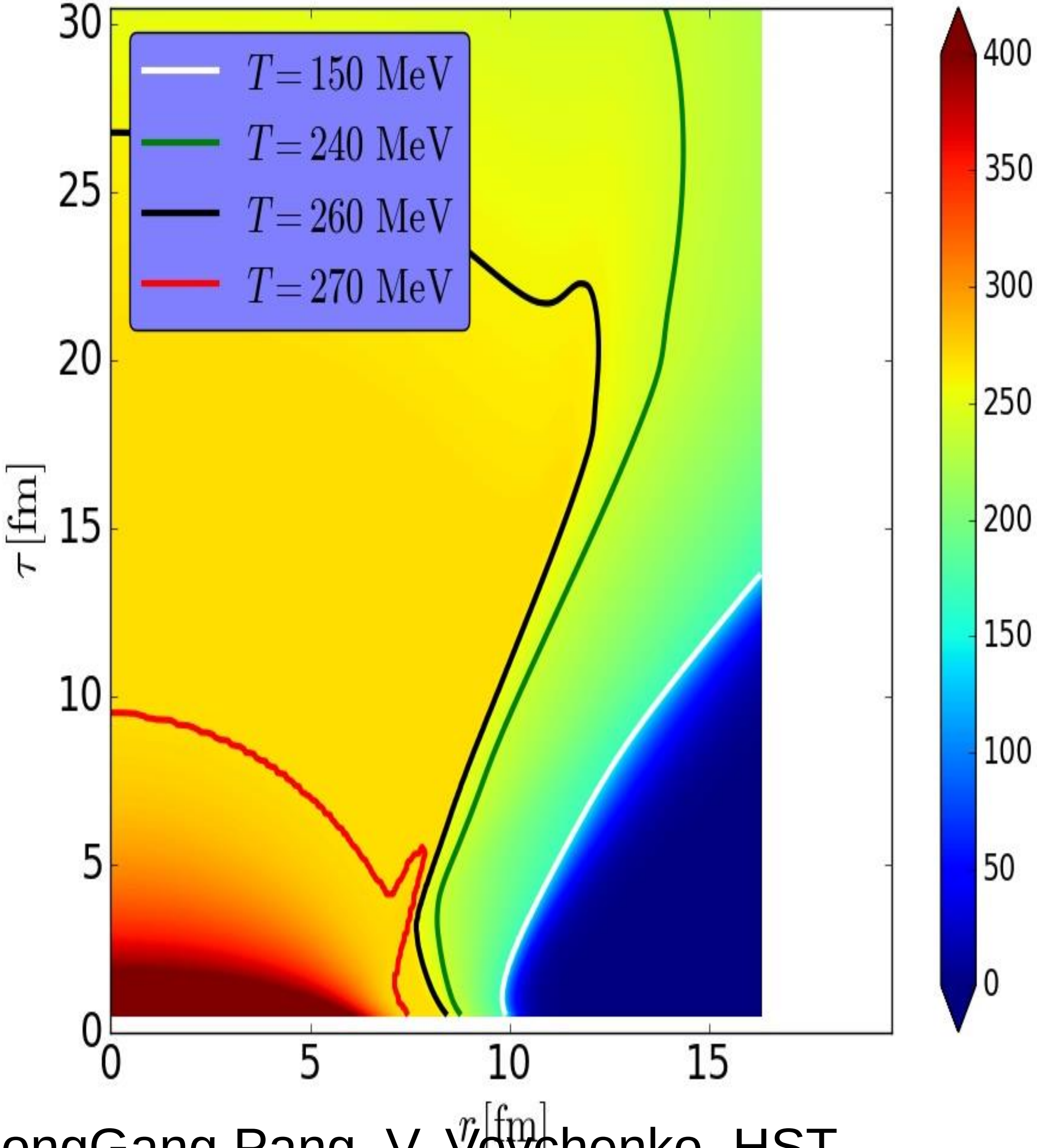


- Event-by-event hydro confirms the de-correlation of anisotropic flow along rapidity
- Brain storms for longitudinal structure of QGP
- Question flow measurements. (Event planes are different with big pseudo-rapidity gap)

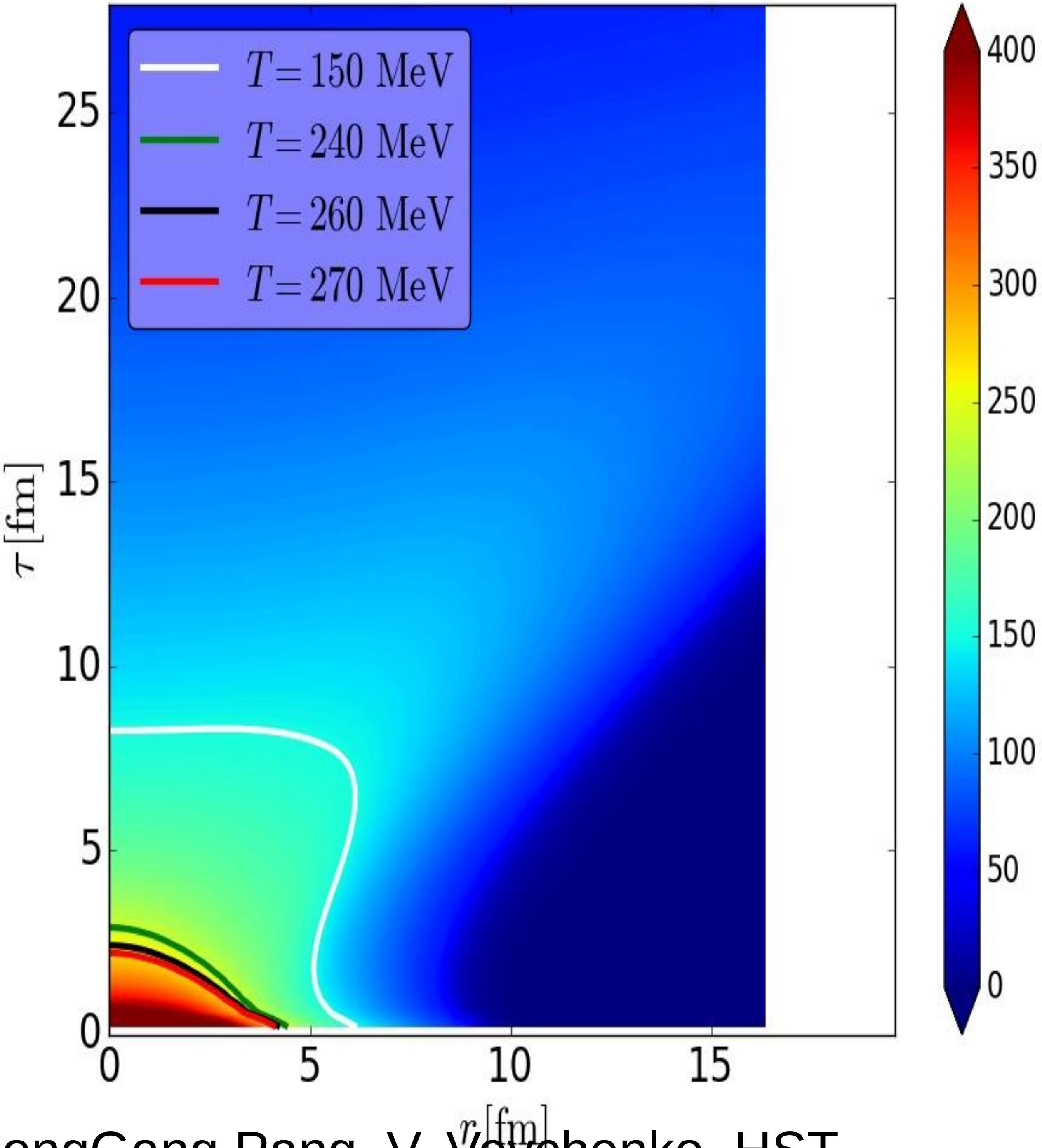
LongGang Pang, Petersen, X.N. Wang



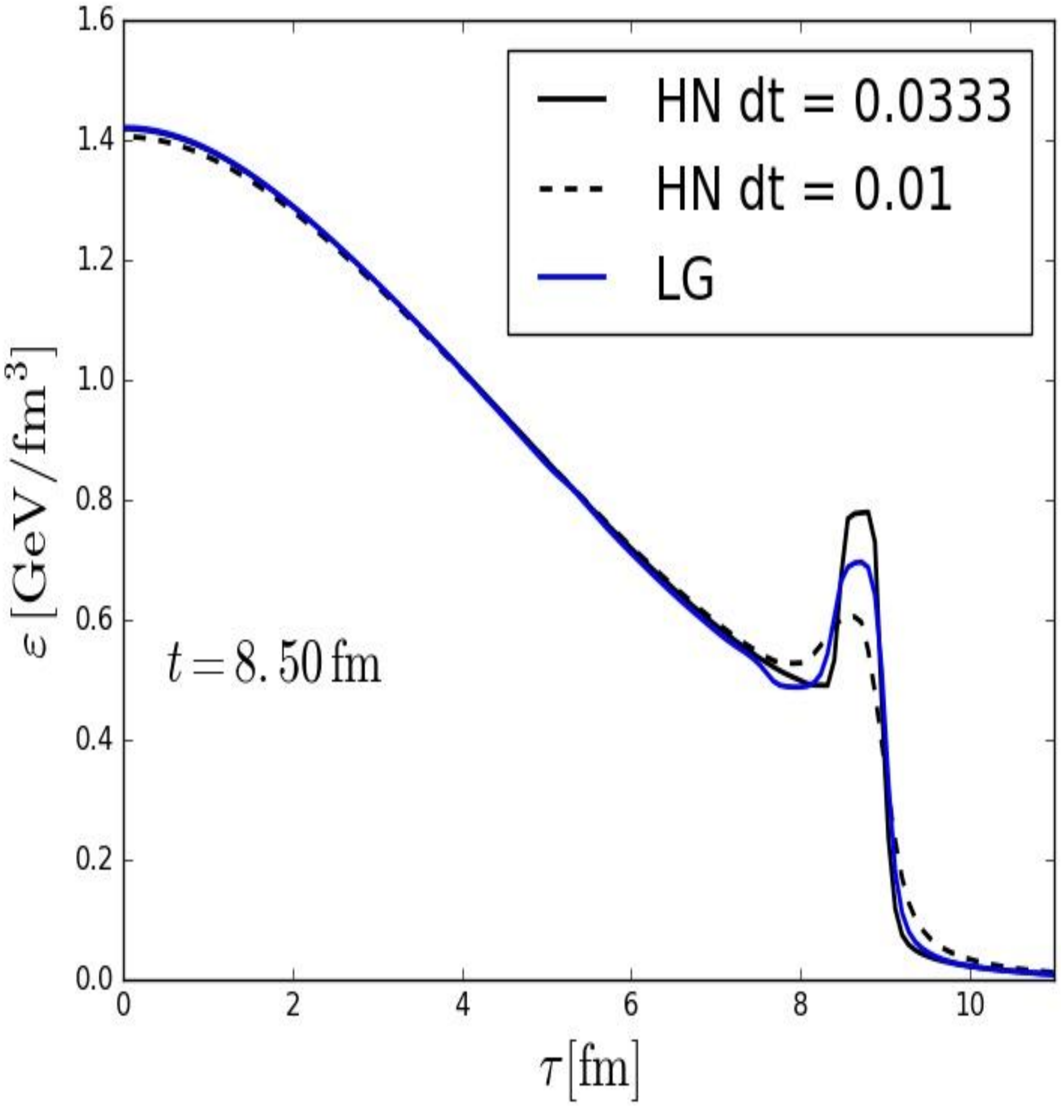
H. Niemi, LongGang Pang, V. Vovchenko, HST



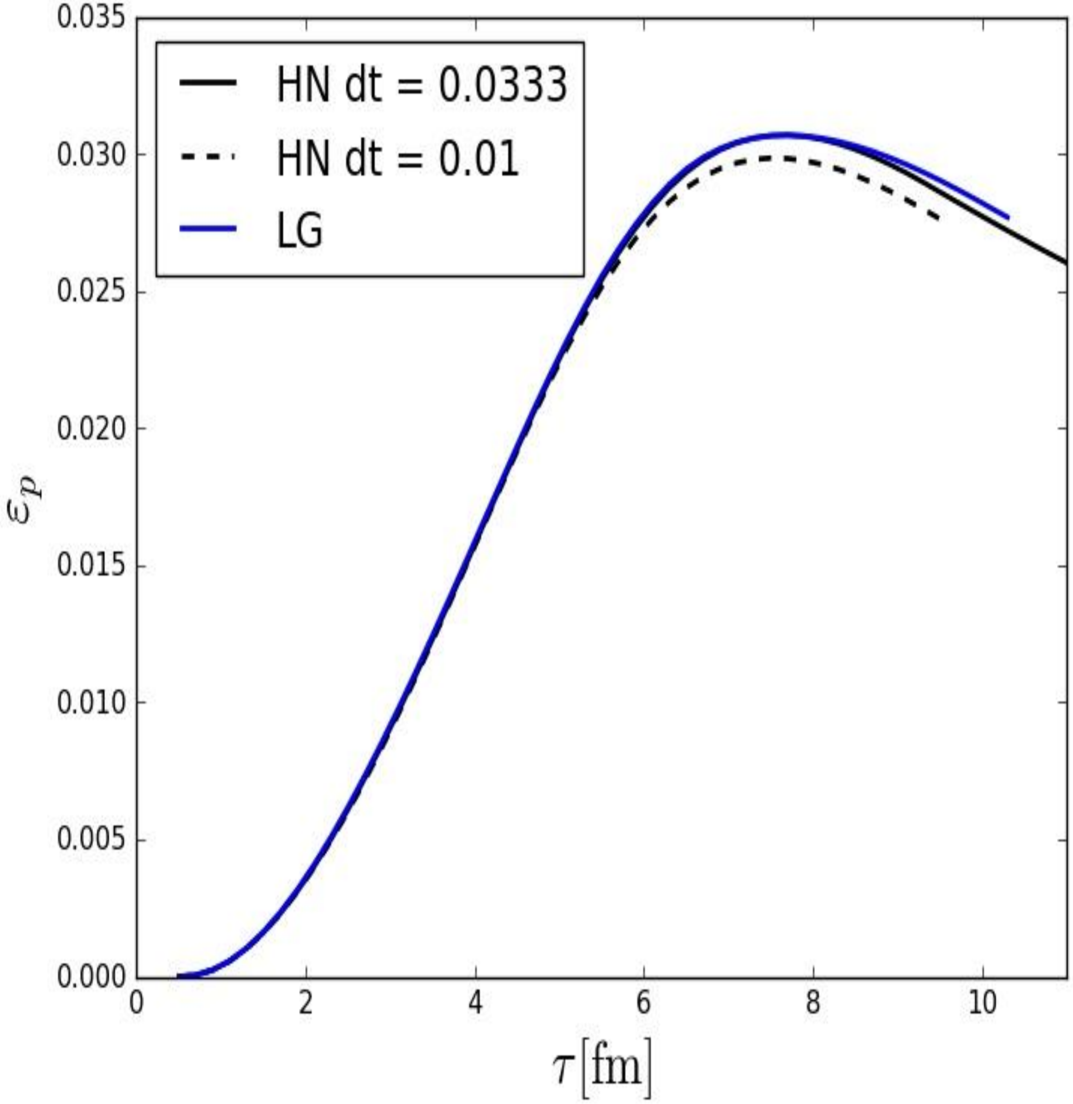
H. Niemi, LongGang Pang, V. Vovchenko, HST



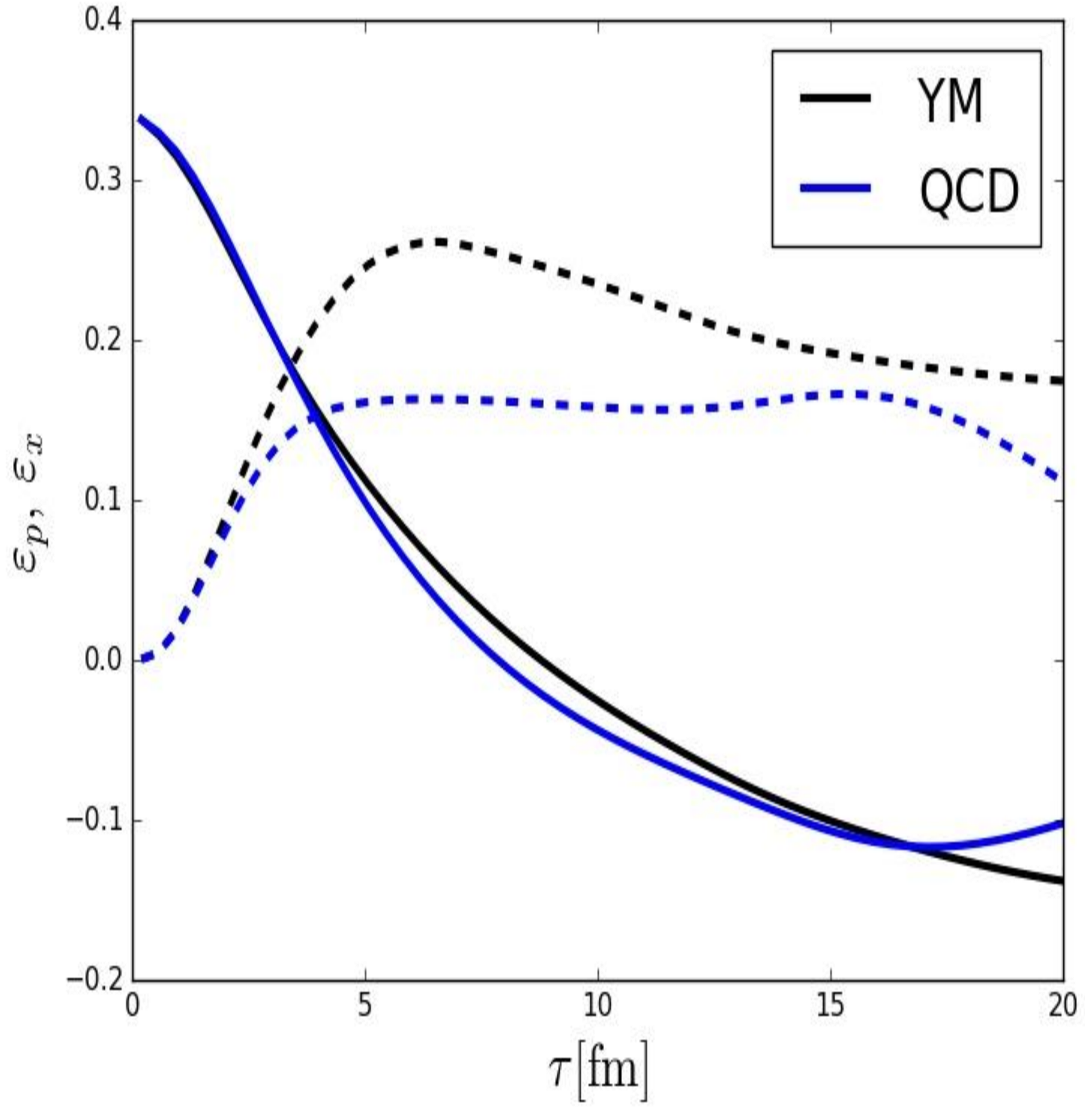
H. Niemi, LongGang Pang, V. Vovchenko, HST



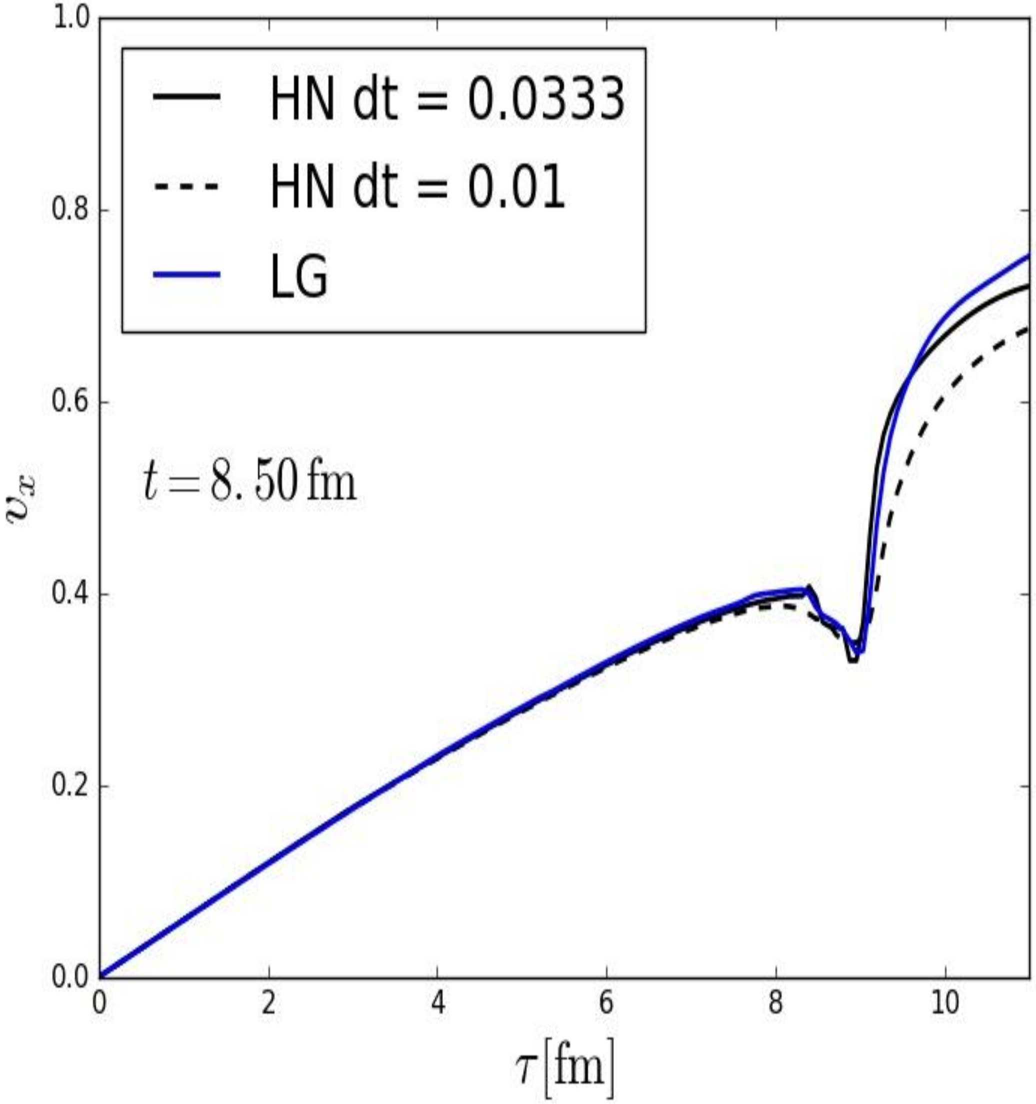
H. Niemi, LongGang Pang, V. Vovchenko, HST



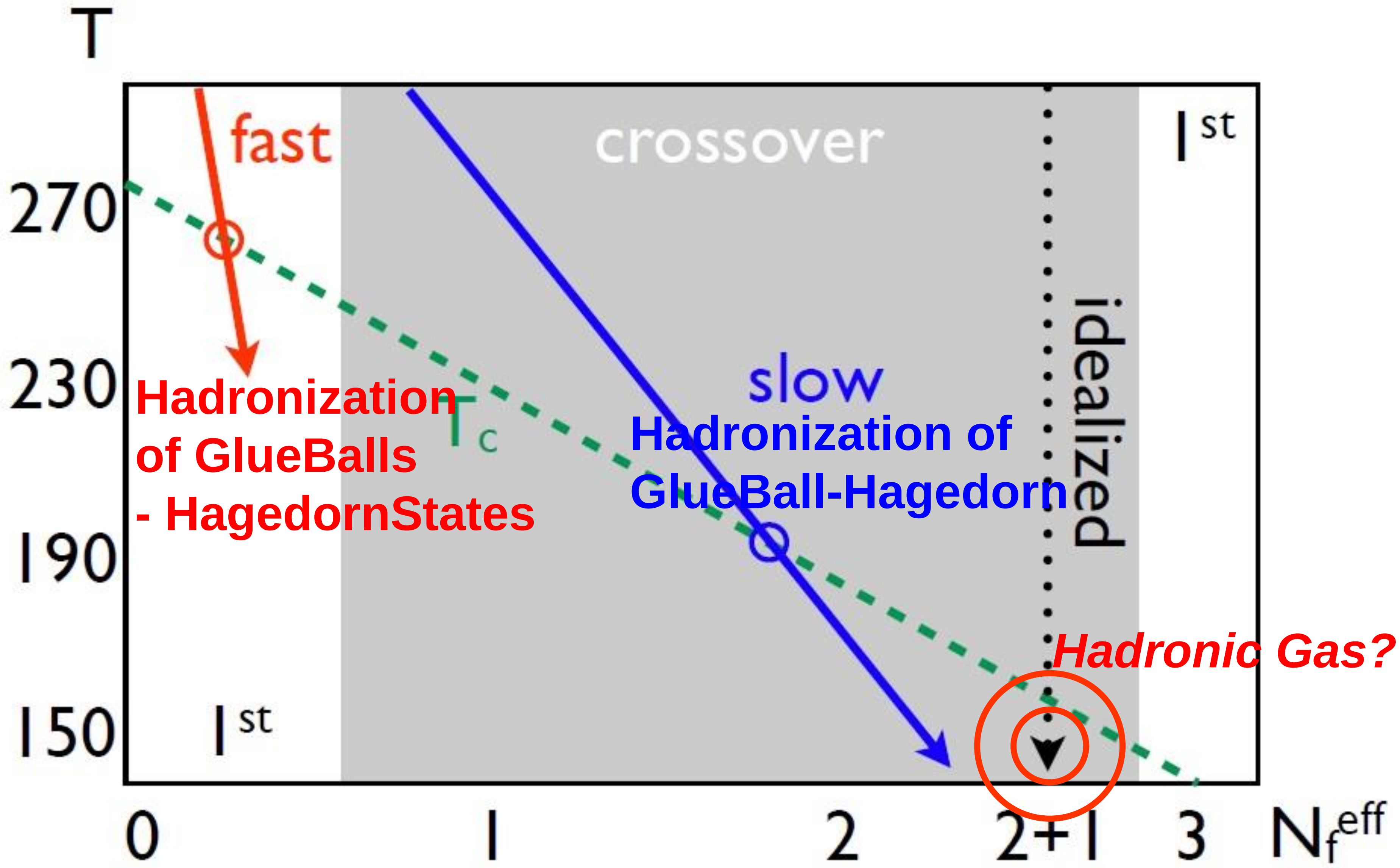
H. Niemi, LongGang Pang, V. Vovchenko, HST



H. Niemi, LongGang Pang, V. Vovchenko, HST



H. Niemi, LongGang Pang, V. Vovchenko, HST

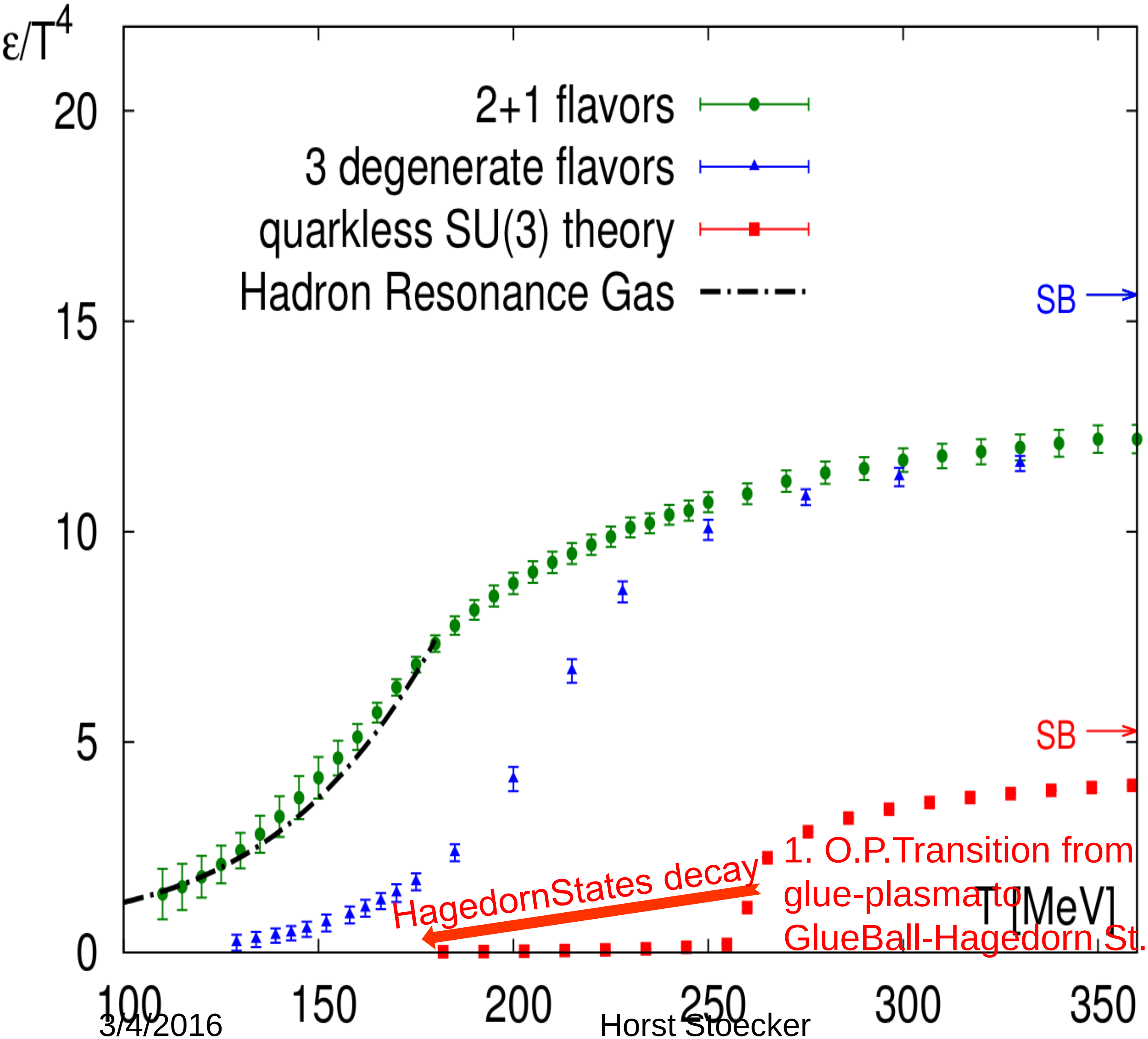


Hadronization of GlueBalls - HagedornStates

Hadronization of GlueBall-Hagedorn

Hadronic Gas?

Pure YM LGT vs. 2+1 flavor Lattice QCD
Energy density (EoS) DIFFERENT for different quark masses



HagedornStates decay

1. O.P.Transition from glue-plasma to GlueBall-Hagedorn St.

Energy density from
Sz. Borsanyi et al., W.P.
Wuppertal-Budapest coll
JHEP 1011, 2010,077;
PLB730, 2014, 99

“physical point” 2+1
T_c.o. = 155 MeV

N_f = 3, $m_{u,d} = m_s$
T_c.o. = 220 MeV

pure gauge YM
T_c = 270 MeV

Quenched: W.B. coll.
JHEP 1207, 2012, 056

Multi-component eigenvolume HRG vs lattice QCD

“Diagonal” EV model

$$p = \frac{\sum_i T n_i}{1 - \sum_i v_i n_i} \qquad \boldsymbol{v_i = \frac{16}{3}\pi r^3}$$

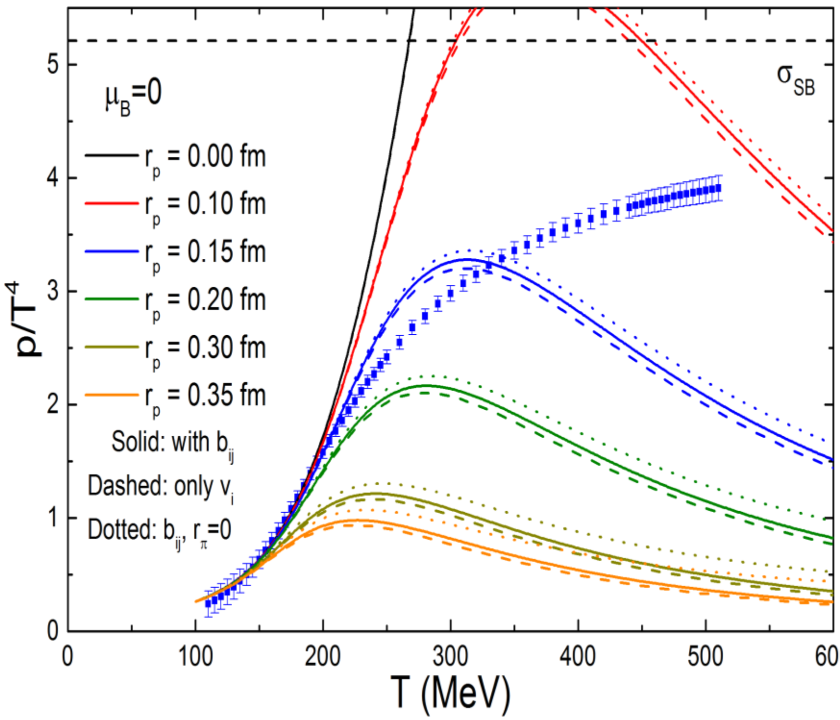
“Crossterms” EV model

$$p = \sum_i \frac{T n_i}{1 - \sum_j \tilde{b}_{ji} n_j} \qquad b_{ij} = \frac{2}{3}\pi\left(r_i + r_j\right)^3$$

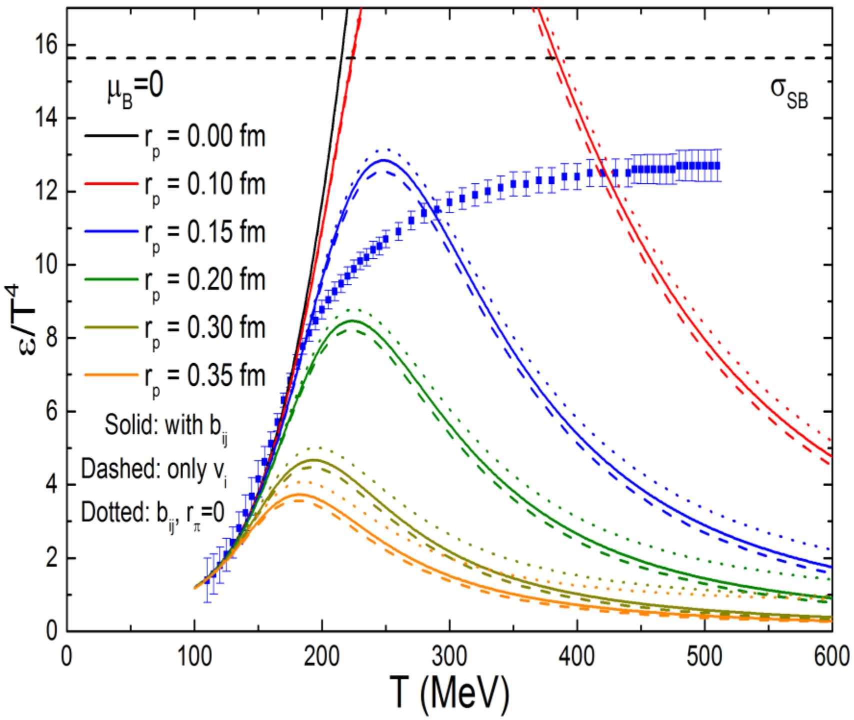
$$\boldsymbol{\tilde{b}_{ij} = \frac{2 b_{ii} b_{ij}}{b_{ii} + b_{jj}}}$$

Bag-model inspired parametrization: $\boldsymbol{r_i \sim m_i^{1/3}}$

pressure



energy density

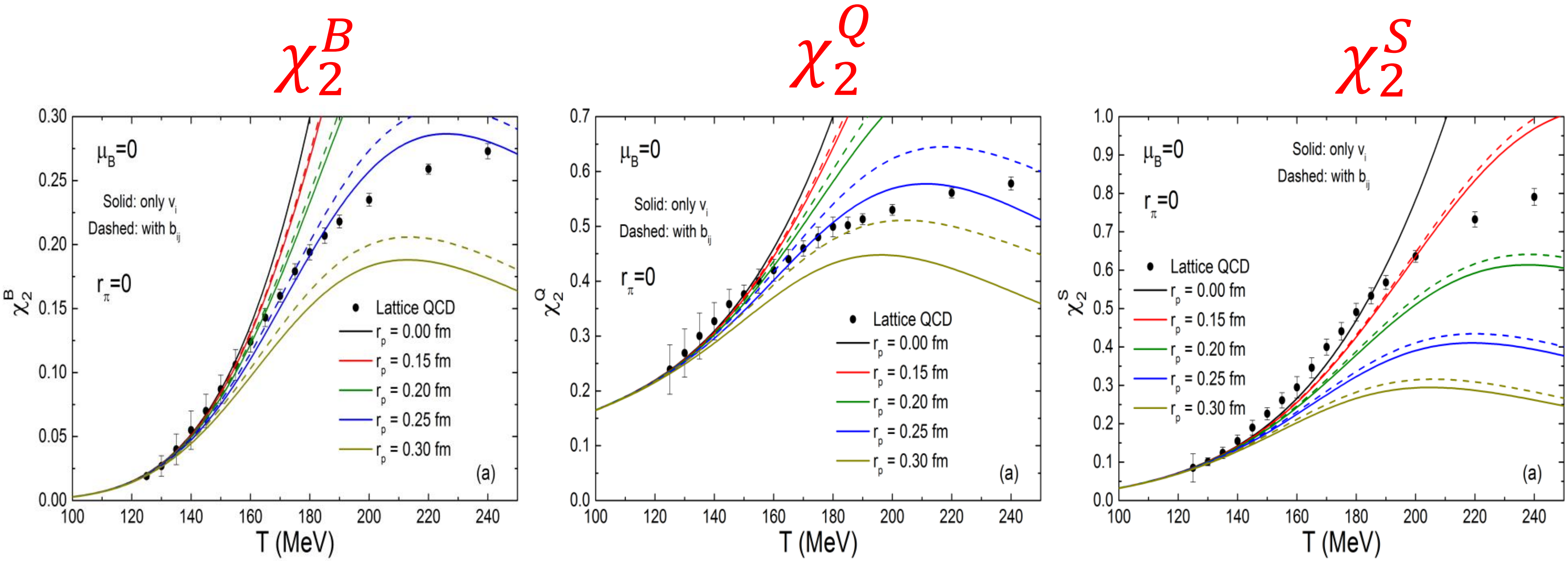


Wuppertal-Budapest Lattice data well described by EV HRG with $r_p = 0.15 - 0.20$ fm up to T=250 MeV

V. Vovchenko, HST

Multi-component bag-eigenvolume HRG vs lattice QCD

Susceptibilities carry information about finer details of the equation of state



r=0 : HRG of point particles
cannot follow lattice data above T=160 MeV
Finite eigenvolumes of hadron bags:
dramatic improvement towards lattice data

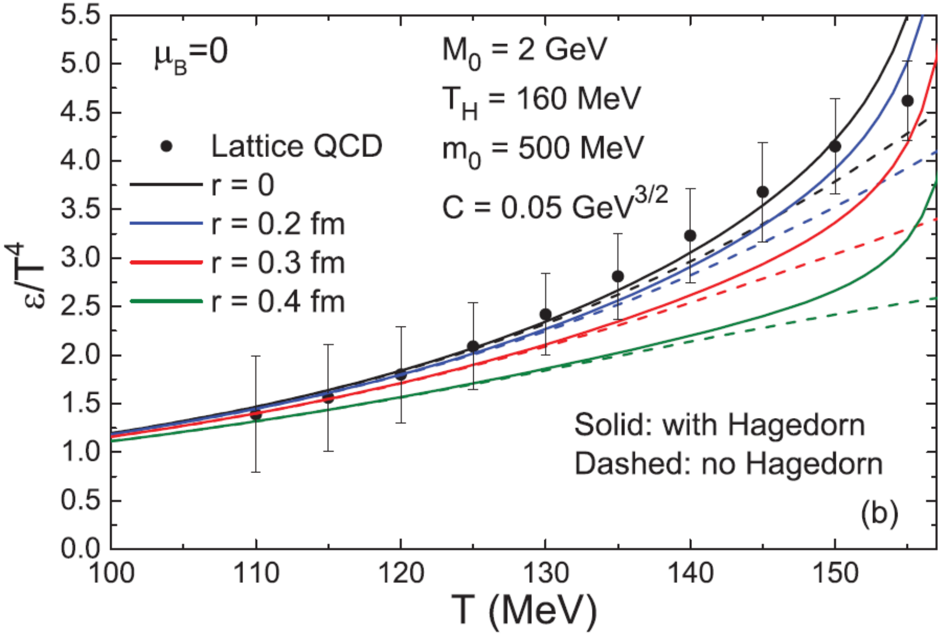
strange vs non-strange hadrons
- different volumes at same mass?

V. Vovchenko, HST, in preparation

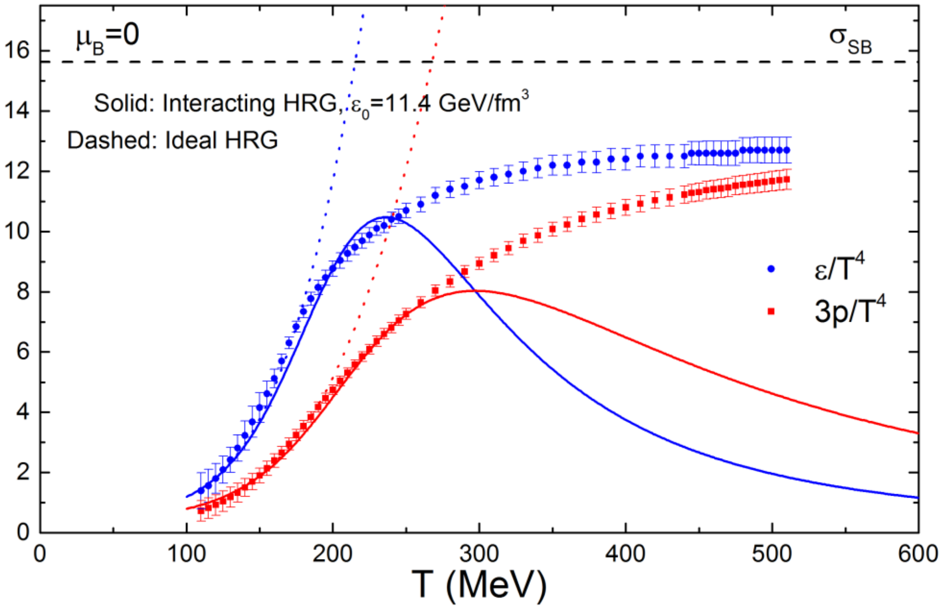
Interacting hadron-resonance gas versus lattice QCD

Vovchenko, Anchishkin, Gorenstein PRC 91, 024905 (2015), left rhs: V. Vovchenko,HST work in prog

Eigenvolume ($r = 0.3$ fm)
+ Hagedorn tower ($T_H = 160$ MeV)



Eigenvolume $\mathbf{v_i = m_i/\varepsilon_0}$



Lattice data clearly require finite eigen-volume of hadrons $\mathbf{v_i = m_i/\varepsilon_0}$

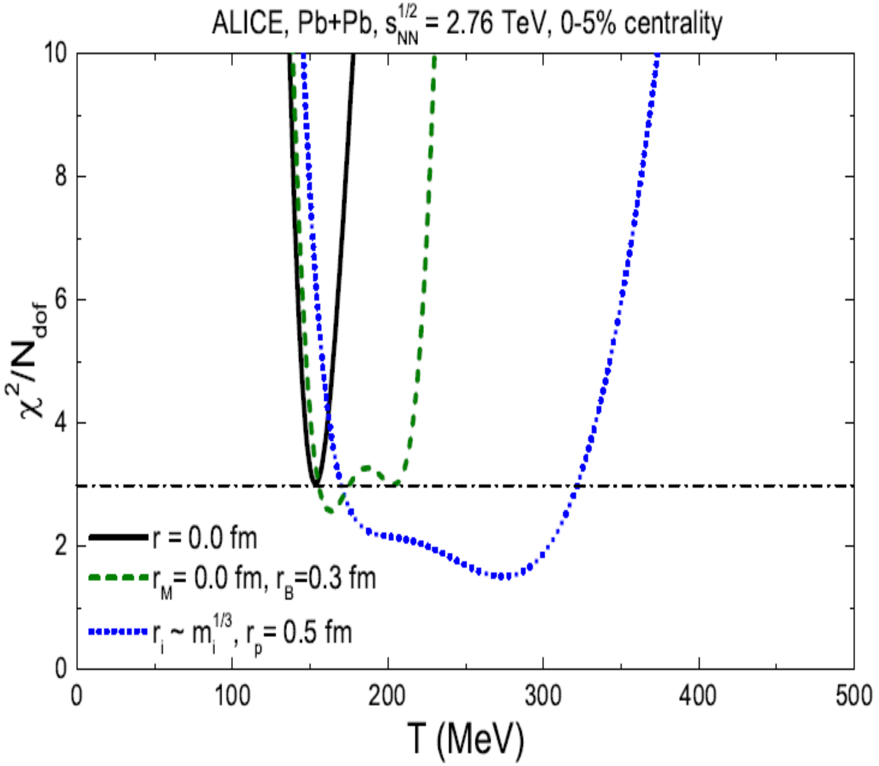
Lattice data fitted by HRG up to $\mathbf{T \sim 250}$ **MeV** **- if** Eigenvolume is respected

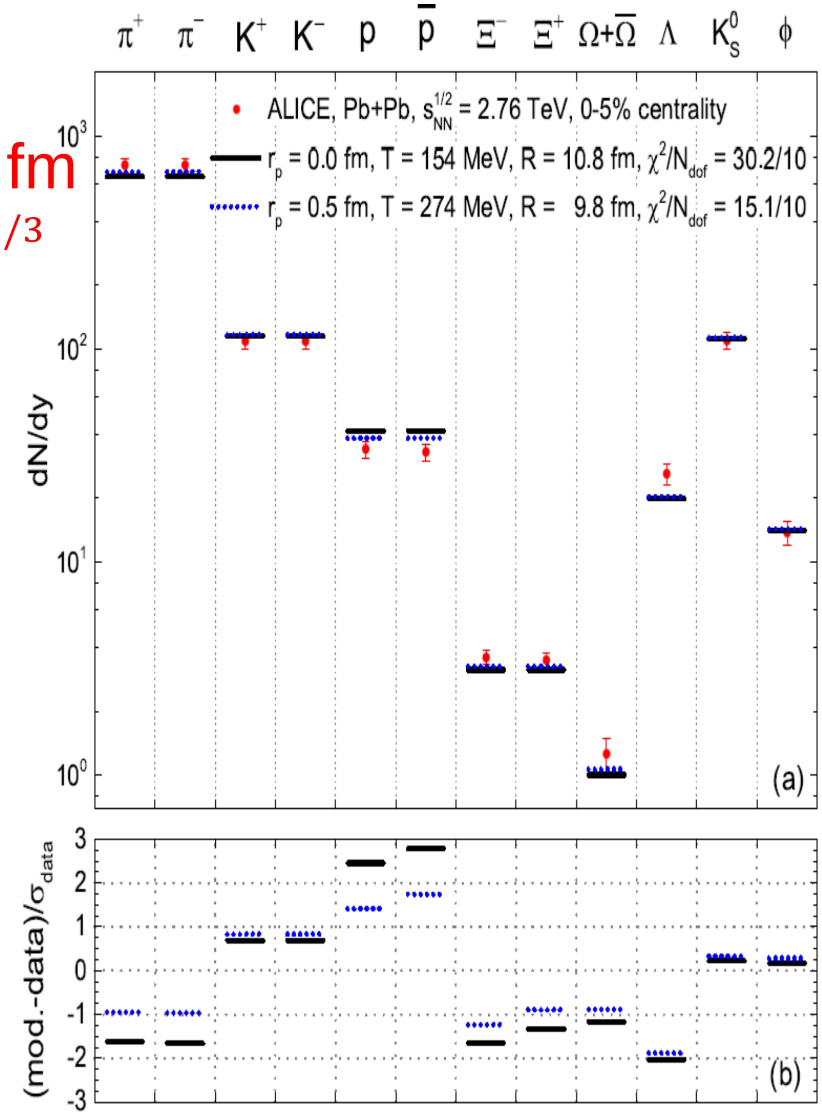
Multi-component eigenvol. HRG vs ALICE hadron yield data

Two eigenvolume parametrizations:

1) Point-like mesons, Baryons $r_B = 0.3$ fm

2) Bag-model inspired EV model: $r_i \sim m_i^{1/3}$





ALICE yield data fit wide temperature range, two different eigenvolumes parame

V. Vovchenko, H. Stoecker, arXiv:1512.08046 [hep-ph]

Multi-component eigenvol. HRG constrained to lattice data

conservative approach: constrain HRG parameters by lattice data

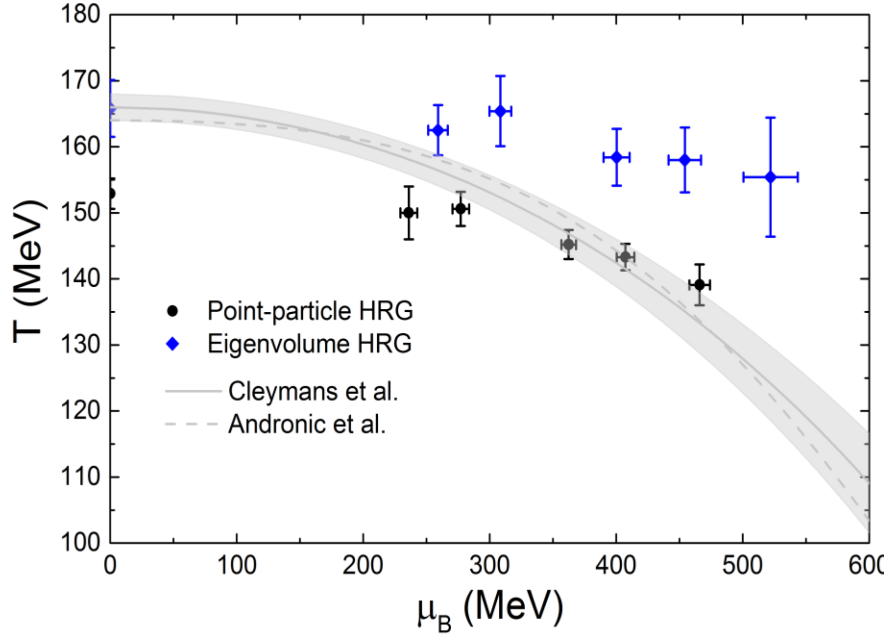
Crossover EoS of QCD: matching HRG low (T,μ) - pert. QCD high (T,μ)

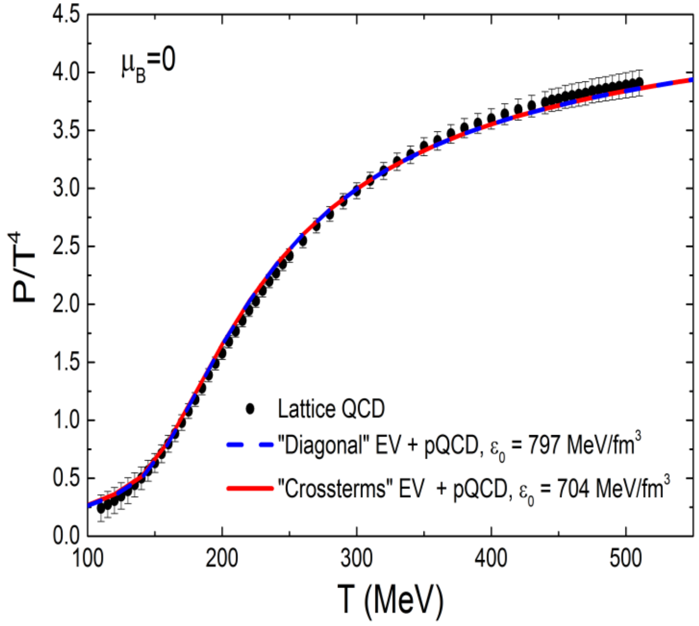
$$p(T,\mu) = [1 - S(T,\mu)]P_{HRG}(T,\mu) + S(T,\mu)P_{pQCD}(T,\mu)$$

Transition from EV HRG ($r_i \sim m_i^{1/3}$) to pQCD at $T_0 \cong 175$ MeV via switching funct

Albright, Kapusta, Young, PRC 90, 024915 (2014)

Fit to yield data at $T < T_0$ with $r_p = 0.43$ fm - Consistent with lattice



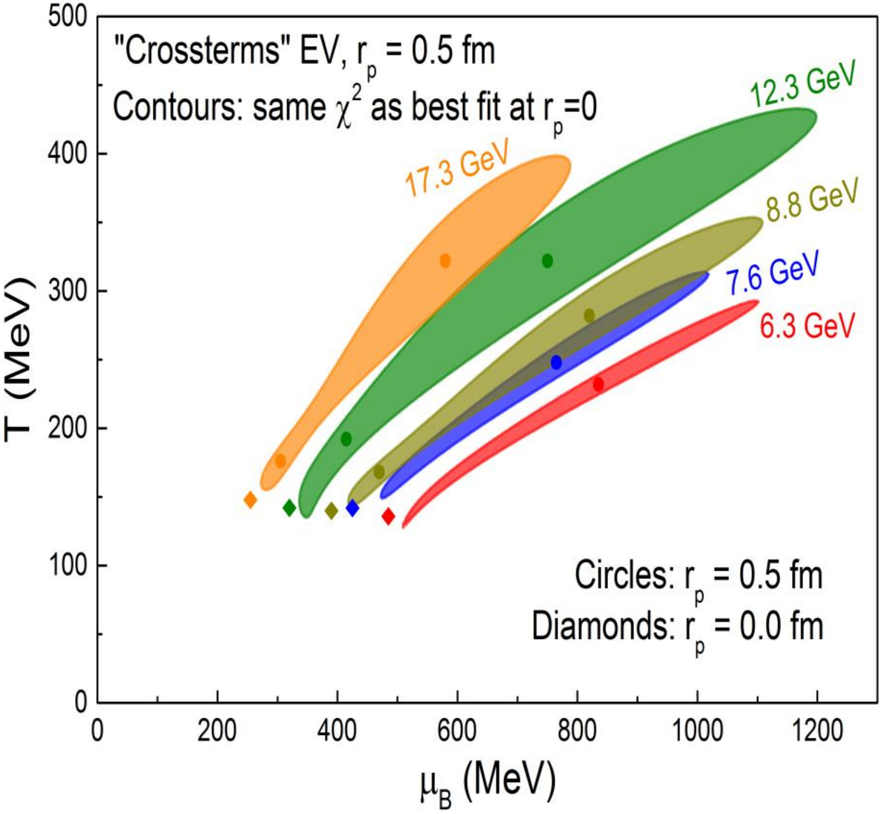


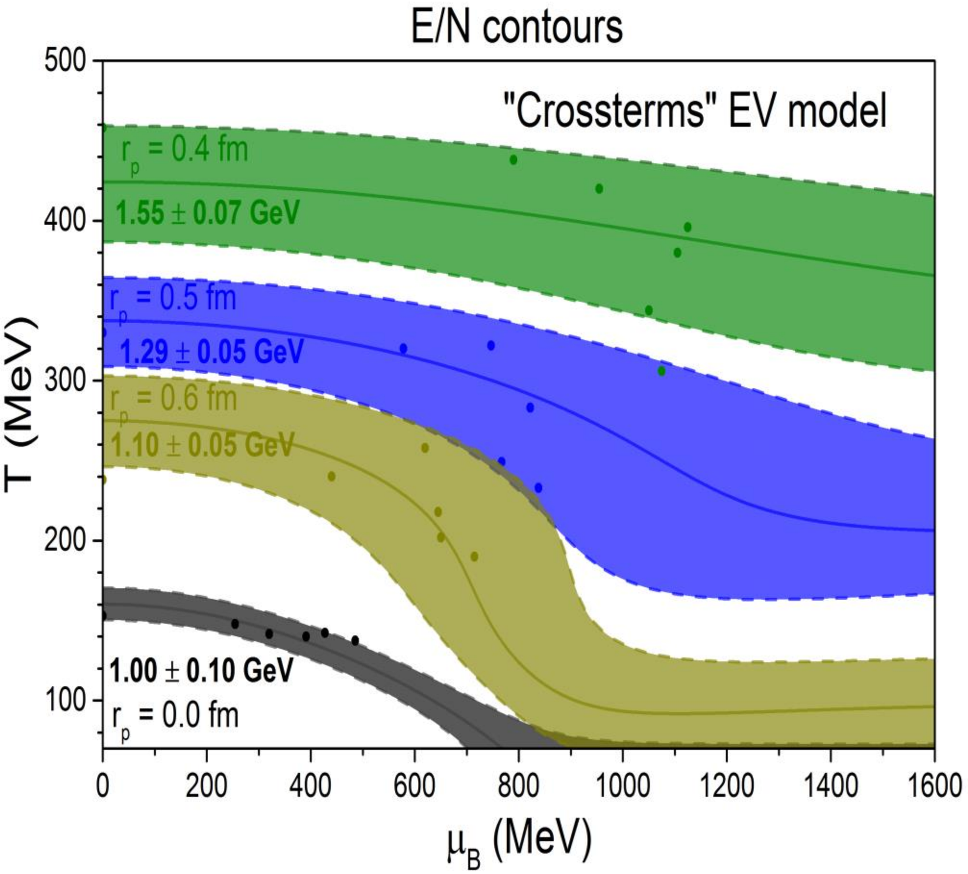
Results: systematically better χ^2, higher freeze-out T and μ, smaller curvature of freeze-out curve

V. Vovchenko, H. Stoecker, in preparation

Multi-component eigenvol. HRG vs NA49 hadron yield data

Bag-model inspired EV model: $r_i \sim m_i^{1/3}$





Chemical Potentials and Temperatures shows large uncertainty !

freeze-out criterion E/N = const. ok, but ‘const.’ depends on chosen eigenvolumes

Can freeze-out T-mu extraction with HRG
in ISENTROPIC Expansion ever be reliable? => Measure S/A, not T !

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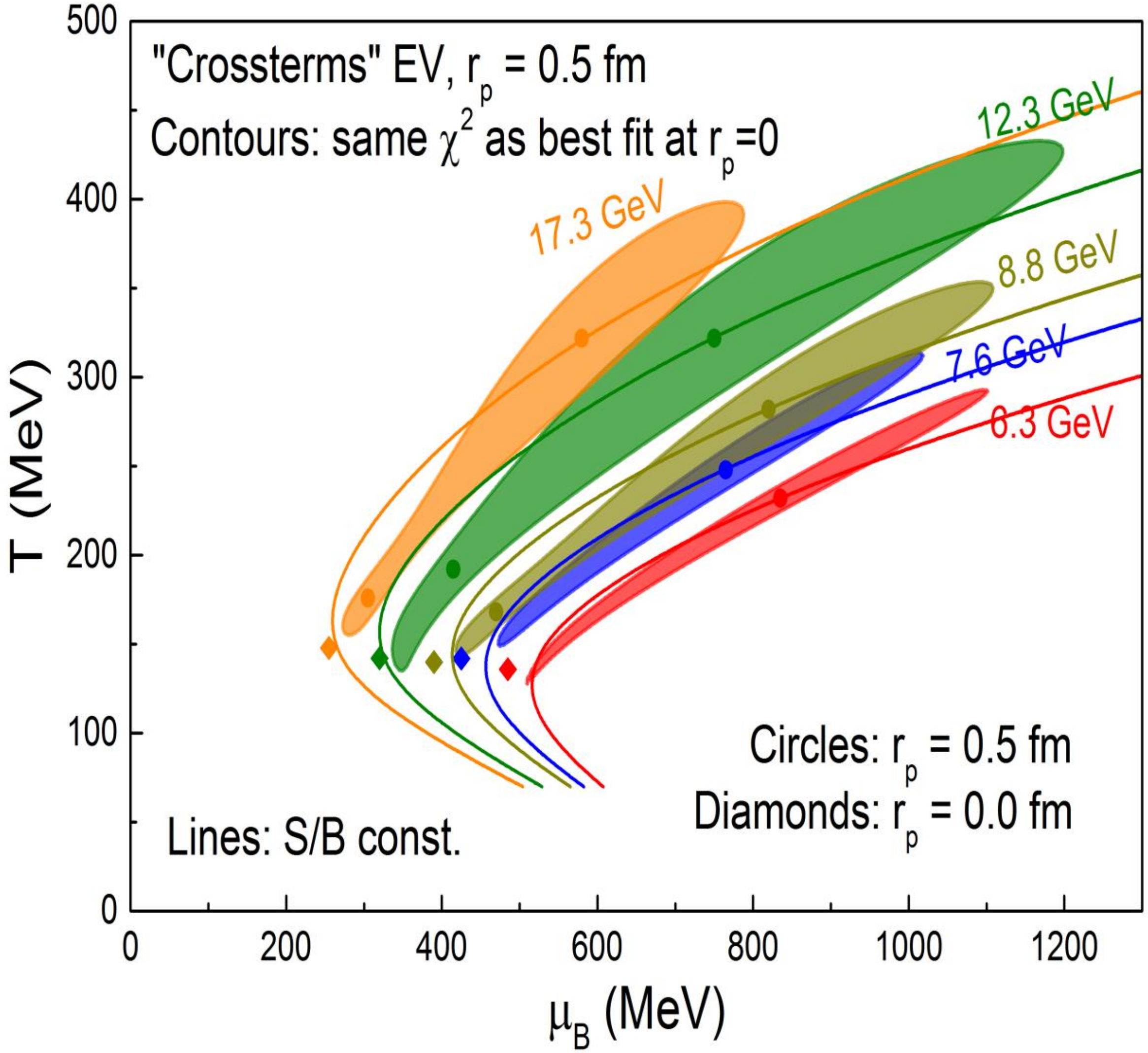
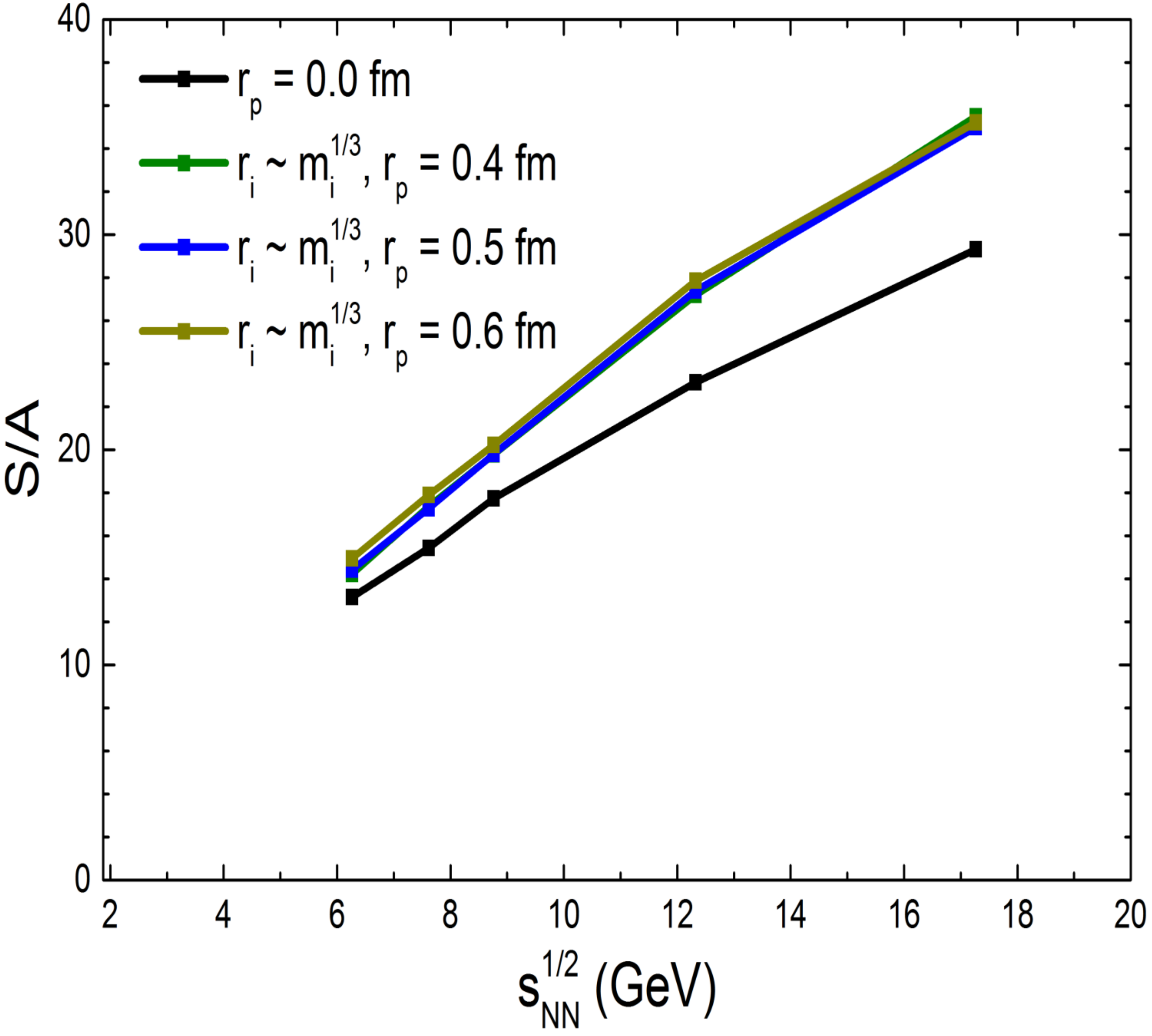
Multi-component eigenvolume HRG vs NA49 hadron yield data



Wide χ^2 minima regions correspond approximately to isentropic curves



VoVchenko: NA49 data allow measurement of S/A= const (energy)!

Signatures for pure glue => glueball scenario

New event-class in high multiplicity pp & pA
at FAIR*, RHIC and LHC

Identification of Glueballs

Lightest Glueball predicted near two states of same Q.N..

“Over population” Predict 2, see 3 states

Glueballs should decay in a flavor-blind fashion.

$$\boxed{\pi\pi : K\bar{K} : \eta\eta : \eta'\eta' : \eta\eta' = 3 : 4 : 1 : 1 : 0}$$

Production Mechanisms:

Certain are expected to by **Glue-rich**, others are Glue-poor. Where do you see them?

Proton-antiproton

Central Production

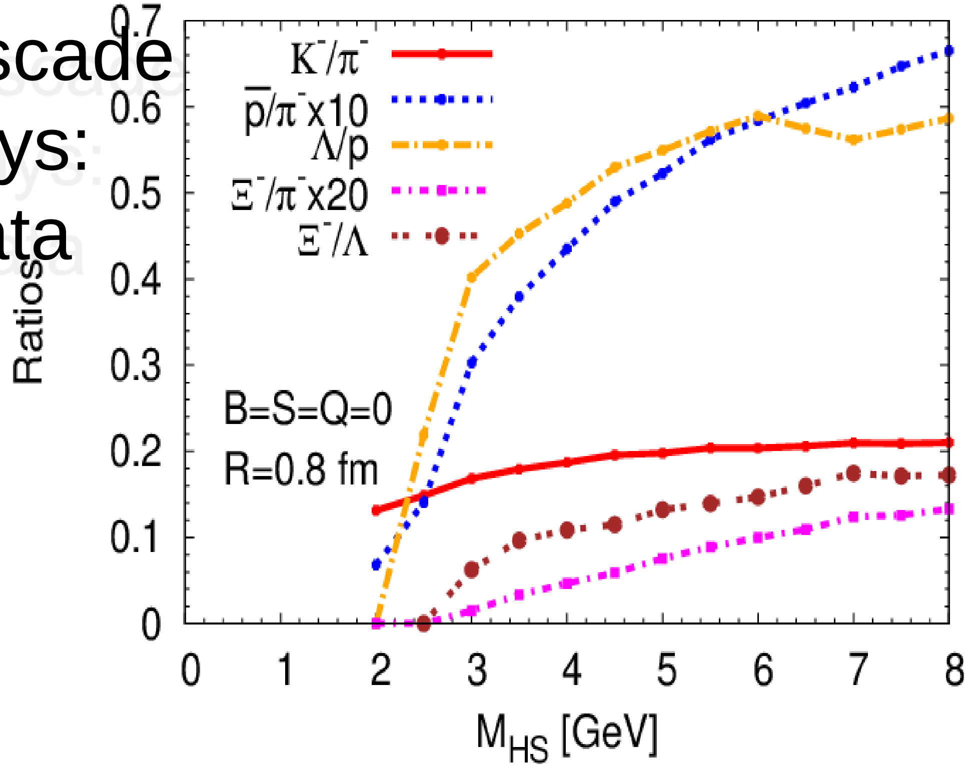
J/ψ decays

Courtesy of Curtis Meyer, Carnegie Mellon, ODU Colloquium

Hagedorn hadronization: cascade of sequential 2-body decays: yields/ratios vs ALICE data

$$\mathrm{p-p}: \sqrt{s_{NN}} = 0.9\,\mathrm{TeV}$$

$$\mathrm{Pb-Pb}: \sqrt{s_{NN}} = 2.8\,\mathrm{TeV}$$



data: ALICE @ LHC

	p-p	Pb-Pb	4 GeV	8 GeV
K^-/π^-	0.123(14)	0.149(16)	0.187	0.210
$\overline{p}/\pi^-$	0.053(6)	0.045(5)	0.043	0.066
Λ/π^-	0.032(4)	0.036(5)	0.021	0.038
$\Lambda/\overline{p}$	0.608(88)	0.78(12)	0.494	0.579
Ξ^-/π^-	0.003(1)	0.0050(6)	0.0023	0.0066
$\Omega^-/\pi^- \cdot 10^{-3}$	—	0.87(17)	0.086	0.560

M.Beitel, K.Gallmeister, C.Greiner, PRC 90 (2014) 045203

Alternate Scenario: pure gauge matter in pp, pA – AA ?

Initial Color Glass Condensate → Glasma thermalizes
fast equilibration of Gluons, slow equil. of quarks
high pressure, entropy gluon plasma
→ fast hydrodynamic expansion of gluon plasma.

↓

1. Order Phase Transition at T_c = 270 MeV of flavorless QCD.

↓

Transition from glue plasma in GlueBall fluid

↓

Glueball-Hagedornstates mix with quarks, decay into Hadrons

Acknowledgements

Transport: Zhou, Seizel, Xu, Nara, Pang, Niemi, Biro, C. Greiner...

Hagedorn: Beitel, Gallmeister, Vovchenko, Hostler, C. Greiner...

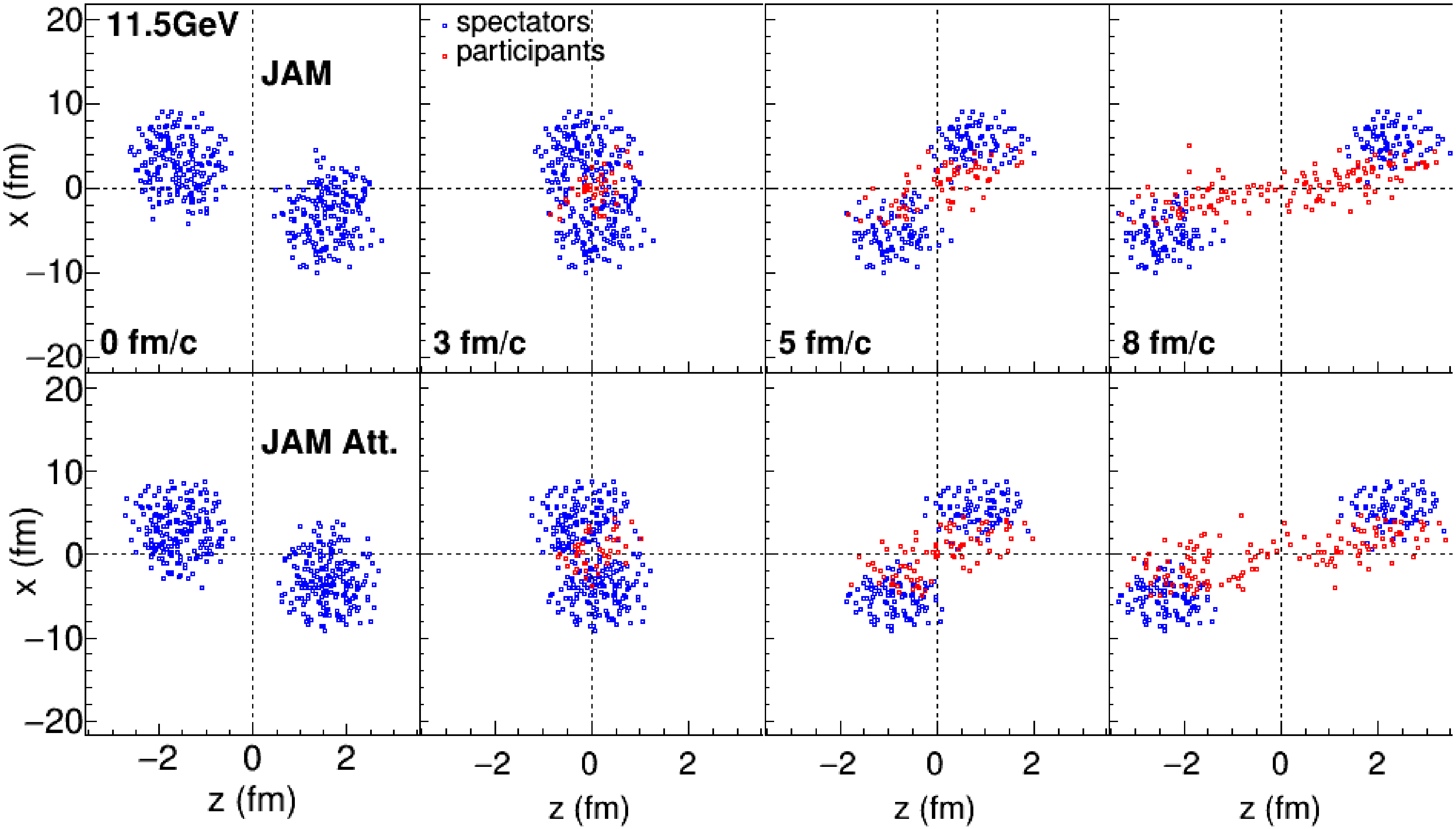
FIAS: Schramm, Struckmeier, Vasak, ...

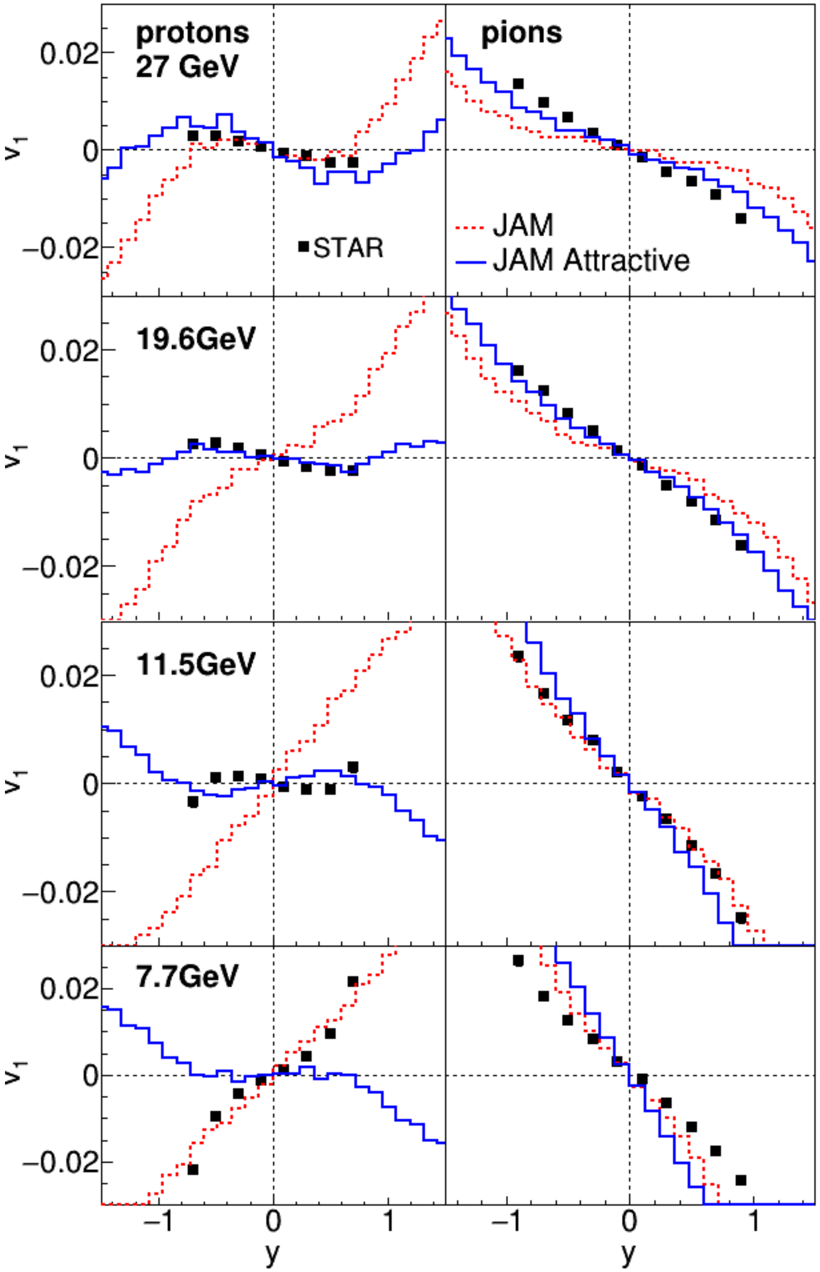
Early phase e-m probes : Vovchenko, Satarov, Gorenstein, Mishustin, Csernai, Raha, Sinha, ...

Lattice : Borsanyi, Fodor, Szabo, Karsch, Panero, Philipsen...

Experiment: Giubellino, Harris, Andronic, Oeschler, PBM, Loizids

Time evolution of density at 11.5GeV





JAM

Akira, Nara & HST

Directed Flow v1
protons
and pions
STAR data